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REPORT ON THE COMPREHENSIVE SURVEY OF THE WATER RESOURCES OF TH--ETC(U)

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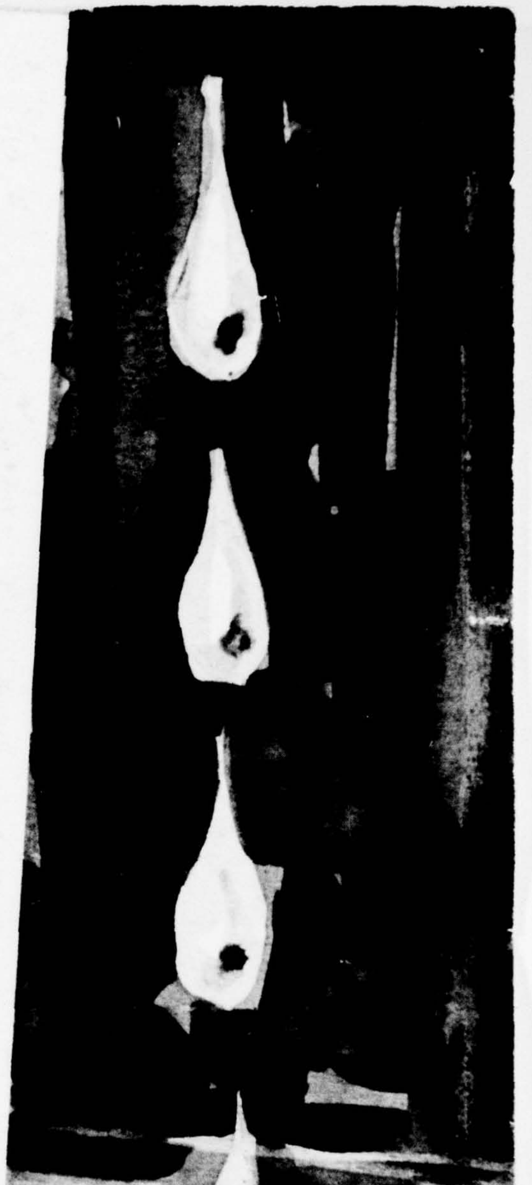
DELAWARE RIVER BASIN REPORT

DEC. 1960

VOL. VII

APPENDIX N. GENERAL GEOLOGY AND GROUND WATER



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REPORT ON THE

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DELAWARE RIVER BASIN.

Volume VII.

APPENDIX N,

Contents: GENERAL GEOLOGY AND GROUND WATER

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10 F. H. Olmsted,
Gerald G. Parker
W. B. Keighton Jr

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U. S. DEPARTMENT OF INTERIOR
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FOR

U. S. ARMY ENGINEER DISTRICT, PHILADELPHIA
CORPS OF ENGINEERS
PHILADELPHIA, PA.

GROUND-WATER RESOURCES OF THE DELAWARE RIVER SERVICE AREA

By F. H. Olmsted, Garald G. Parker, and W. B. Keighton, Jr.

with special sections

By N. M. Perlmutter and R. V. Cushman

1959

A report by the U. S. Geological Survey for
and in cooperation with the Corps of Engineers,
Philadelphia District, as a guide to the better
understanding of the Delaware River service area.

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SUMMARY

The Delaware River basin service area, as considered in this report, occupies a total area of about 30,000 square miles, of which only 12,865 square miles are in the basin proper. The area includes parts of Connecticut, Delaware, Maryland, New Jersey, New York, and Pennsylvania. Use of water in this highly important region is increasing rapidly, and ground-water supplies constitute a small but locally very significant part of the total supplies.

The Delaware River basin service area occupies parts of two major physiographic divisions, separated by the Fall Line, which extends northeasterly across the region Wilmington, Del., Philadelphia, Pa., Trenton, N. J., and New York, N. Y. The Atlantic Plain division, or Coastal Plain as its emerged part is called, lies southeast of the Fall Line. The Coastal Plain is underlain by a thick wedge of seaward-dipping unconsolidated deposits of alternating permeable aquifers composed of sand and some gravel and relatively impermeable aquicludes composed of clay, silt, and marl. Northwest of the Fall Line is the Appalachian Highlands division, characterized by ridges, valleys, uplands, and plateaus. The bedrock is consolidated, complex in composition and structure, and generally yields little water to wells, compared to the unconsolidated aquifers of the Coastal Plain. The northern half of the region described has been glaciated and in places contains glacial outwash which constitutes an excellent aquifer.

As a rough approximation, given only to indicate order of magnitude, the potential ground-water supply in the Coastal Plain part of the Delaware River basin is considered equal to the ground-water discharge to streams--about 1,600 mgd in an area of 2,750 square miles. Because of practical limitations, chiefly economic, it is estimated that only about half this total--or about 800 mgd--can be developed. Present use (1951-56 average) is about 210 mgd, but the net ground-water discharge is even less, because part of the water pumped is not consumed and returns to the aquifers.

Aquifers in the nonmarine sediments of Cretaceous age--the lowest group of aquifers in the Coastal-Plain wedge of deposits--yield the largest proportion of the total ground-water pumpage at present (slightly more than half in 1951-56), but the deposits of Quaternary age are becoming increasingly important, and the Cohansey sand offers perhaps the greatest potential for future development.

As in the Coastal Plain, the potential ground-water supply in the Appalachian Highlands is considered equal to the ground-water discharge to streams--4,400 ± 500 mgd. However, it is believed that only a small fraction of this potential supply can be developed feasibly. Instead,

development of surface-water supplies will continue to be dominant in the Highlands, although large ground-water supplies may be developed locally, as in the glacial outwash along some of the major streams. In many places, wells developed in permeable deposits near streams may induce recharge at rates far greater than the natural recharge rate, and individual sustained yields of about 500-1,000 gpm are not uncommon. Such developments of large ground-water supplies will be at the expense of streamflow, for ground water and surface water are each part of the same total resource.

Ground water suitable for most uses may be developed, at least in small quantities, almost anywhere in the basin. In the Coastal Plain large quantities of fresh ground water can generally be developed except near the ocean and Delaware Bay, but even to this general rule there are exceptions. For instance, where thick impermeable aquicludes intervene between the salt water of the ocean or bay and fresh water of deeper aquifers sizable supplies of good water can be developed--as in the "800-foot" sand at Atlantic City, N. J. However, salty water extends inland to different and varying distances in each aquifer; for example, water in excess of 250 ppm as chloride is believed to underlie about half the entire State of New Jersey in the Cretaceous artesian aquifers.

In the Coastal Plain of the area reported upon, numerous fresh-water well supplies have become salty. For the most part this represents encroachment from the modern sea; however, some of the salty water originated in the geologic past as residual salinity never flushed out in later times. The encroachment is due in part to a slow world-wide rise of sea level (6 inches in this area since 1930), but mostly it is due to pumping too near a body of salty ground or surface water. Some of the encroachment may be due largely, as it was at Lewes, Del., and Newark, N. J., to salt water being introduced to a former fresh-water domain through dredging operations. Extensive pumping of wells near the existing salt-water--fresh-water interfaces in aquifers, or deep dredging of river or canal channels that would, in effect, become inland arms of the sea, would probably accelerate salt-water encroachment and either ruin or greatly depreciate the value of many existing ground-water supplies of the Coastal Plain.

Although fresh ground water in the Coastal Plain aquifers is generally good to excellent, there are some places where the ground water is hard and requires softening for many uses. The greatest quality problem (apart from salt-water contamination) is the irregular and largely unpredictable presence of water high in iron and sometimes manganese.

In the Appalachian Highlands most ground waters are of satisfactory chemical quality for most uses, although the carbonate rocks generally yield hard water, the sulfate content is high in some formations, particularly in the anthracite coal regions, and objectionable quantities

of iron occur locally in several types of rocks and deposits. Wells in very shallow aquifers, especially dug wells, sometimes become contaminated by surface sources.

In Fairfield County, Conn., ground-water supplies are obtained from various crystalline bedrock formations and from unconsolidated glacial deposits. Average yield of wells in bedrock is about 8-10 gpm, but yields of wells in some of the coarse-grained stratified glacial deposits commonly are several hundred gallons per minute. Of the average precipitation of about 48 inches, 26 inches is discharged as direct and base runoff in streams, and the remaining 22 inches is lost by evapotranspiration. Encroachment of poor-quality water has occurred in the glacial outwash in the coastal area of Bridgeport.

In Dutchess, Orange, Putnam, Rockland, Ulster, and Westchester Counties, N. Y., ground water occurs in the same general rock types as those in the glaciated, northern half of the Delaware River basin. Highest yields are obtained from the glacial deposits; yields from sandstone and shale aquifers in the Newark group (largely in Rockland County) commonly exceed 100 gpm per well; the lowest yields generally are from crystalline bedrock where average yield per well is less than 50 gpm.

On Long Island, N. Y., large supplies of ground water are available from unconsolidated deposits comprising several aquifers of Pleistocene age and the Magothy formation and the Lloyd sand member of the Raritan formation, both of Cretaceous age. The total quantity of ground water available for perennial use is not known, although it is less than the average annual return flow to the ocean of 1,500 mgd. Present consumptive use of ground water (estimated to be half the total withdrawal) is about 12 percent of the average annual return flow and about 19 percent of the return flow during the driest year to be expected. Although this suggests the possibility of considerable additional development, rational plans of development will be required to prevent excessive pumping near the shore which would result in salt-water encroachment.

INTRODUCTION

This report was prepared in response to a request from the Corps of Engineers for a report on the ground-water resources of the Delaware River service area. The data herein summarized have been gathered chiefly as a result of many investigations by the U. S. Geological Survey in cooperation with the States of Delaware, New Jersey, New York, and Pennsylvania and with a large number of smaller political divisions and other agencies (including other Federal agencies) over many years. The work requested by the Corps of Engineers as a part of the Delaware River basin project was an important, but very small part of this total effort.

The report was written under the immediate superivision of Garald G. Parker, project hydrologist, and under the general supervision of Charles C. McDonald, chief, General Hydrology Branch. The Geological Survey field offices concerned with the Delaware River service area contributed data and made special studies. Ground-water data were furnished, and special hydrologic studies were made, for Delaware by William C. Rasmusen; for New Jersey by Henry C. Barksdale, Allen Sinnott, Paul B. Seaber, Solomon M. Lang, and Leo A. Jablonski; for Pennsylvania by David W. Greenman, Donald R. Rima, Norman H. Blanchard, Jr., and William N. Lockwood; and for New York by Joseph E. Upson, George C. Taylor, Jr., Nathaniel M. Perlmutter, Edward H. Salvas, Julian Soren, and John Isbister. Quality-of-water data for Delaware, New Jersey, and Pennaylvania were supplied by Norman H. Beamer, and for New York by Felix H. Pauszek.

Additional geologic information was furnished by Carlyle Gray, state geologist of Pennsylvania; Meredith E. Johnson, state geologist of New Jersey until 1958, and his successor, Kemble Widmer; Johan J. Groot, state geologist of Delaware; Horace G. Richards, Philadelphia Academy of Natural Sciences; Edward H. Watson and Lincoln Dryden of Bryn Mawr College; Bradford Willard of Lehigh University; Herbert P. Woodward of Rutgers University; and Paul MacClintock of Princeton University. Horace G. Richards assisted in the study of the geology of the Coastal Plain, and interpretations of the stratigraphy of that important region are based largely on his work.

Federal agencies that contributed data, maps, or file material include the Corps of Engineers, Col. Allen F. Clark, district engineer to December 1, 1957, and his successor, Col. William F. Powers; the Soil Conservation Service, Fred H. Larson, head, Engineering Unit; the Public Health Service, Sylvan C. Martin, regional engineer; and the Weather Bureau, William E. Hiatt, chief, Hydrologic Services Division.

Others, far too numerous to mention, including consulting engineers, city, county, State, and other officials, contributed ideas and data.

The writers have drawn freely on the data and conclusions of many reports by the Geological Survey and other agencies and individuals. No attempt is made to present ground-water and geologic information for all the Delaware River basin in the detail that some of these reports provide for parts of the area; instead the general subject matter in these reports is summarized briefly. Basic to the ideas and conclusions presented in this report are the contributions of the several authors who wrote assigned parts of an unpublished 246-page report in 1957 that is a predecessor of this report. That report is largely the work of the following authors listed alphabetically: James K. Culbertson, Garald G. Parker, Nathaniel M. Perlmutter, Donald R. Rima, William C. Rasmussen, and Edward H. Salvas. Also the present writers have drawn much information and important conclusions from a report, published in 1958 by the New Jersey Department of Conservation and Economic Development, entitled "Ground-Water Resources in the Tri-State Region Adjacent to the Lower Delaware River". That report, which contains the most comprehensive treatment of the ground-water resources of the lower part of the Delaware River basin, was prepared by Henry C. Barksdale, David W. Greenman, Solomon M. Lang, George S. Hilton, and Donald E. Outlaw.

Most of the present report has been abstracted and somewhat modified from a longer and more inclusive report dealing with the broad aspects of the hydrology of the Delaware River basin.

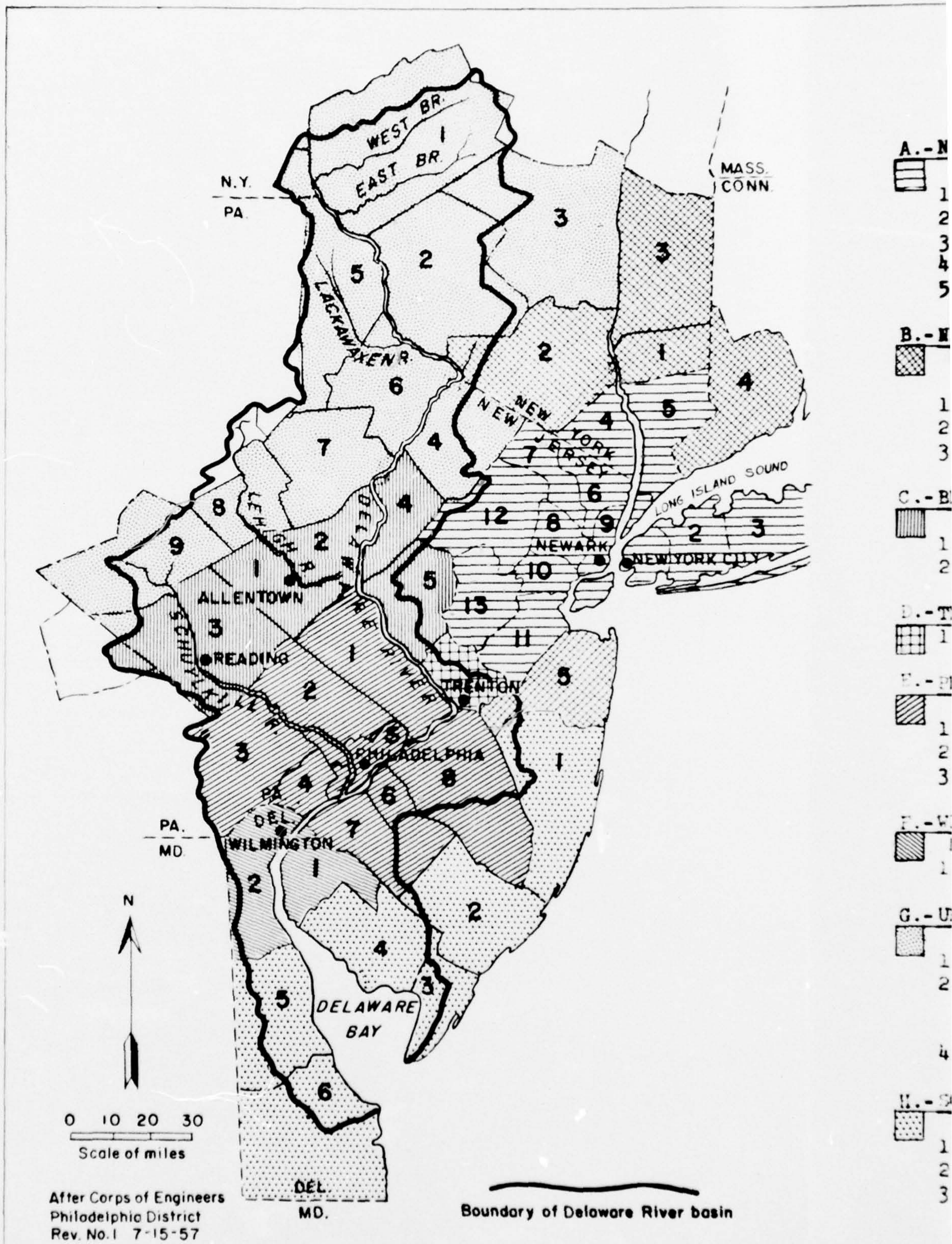
As defined herein, the Delaware River service area covers about 30,000 square miles of which only 12,865 square miles are in the basin proper. Besides the basin itself, which includes parts of New York, Pennsylvania, New Jersey, Delaware, and a small tip of Maryland, the area comprises Fairfield County, Conn.; New York City and Long Island, and Dutchess, Orange, Putnam, Rockland, Ulster, and Westchester Counties, N. Y.; and all of New Jersey and Delaware. The service area and its subdivisions, classified by the Corps of Engineers according to county groups, are shown on plate 1. Total population of the area in 1950 (last U. S. Census) was about 20 million; approximately 6 million people lived within the basin, and of these about 3.7 million lived in the Philadelphia metropolitan area. The population is growing rapidly, especially in the urban and suburban areas; water demands are growing even more rapidly and are creating problems that require comprehensive plans and programs for their solution.

Ground-water sources now furnish a minor, but locally important part of the total water withdrawn in the Delaware River service area. Of a basinwide withdrawal of 6,100 mgd (million gallons per day) in 1955 (not including water for hydroelectric plants) ground-water sources supplied 340 mgd--5.6 percent of the total (Kammerer, 1957, p. 9; revised 1958). Ground water furnishes the largest proportion of total withdrawals for irrigation, rural, and small-scale municipal uses--types of uses where the demand is dispersed rather than concentrated in relatively small

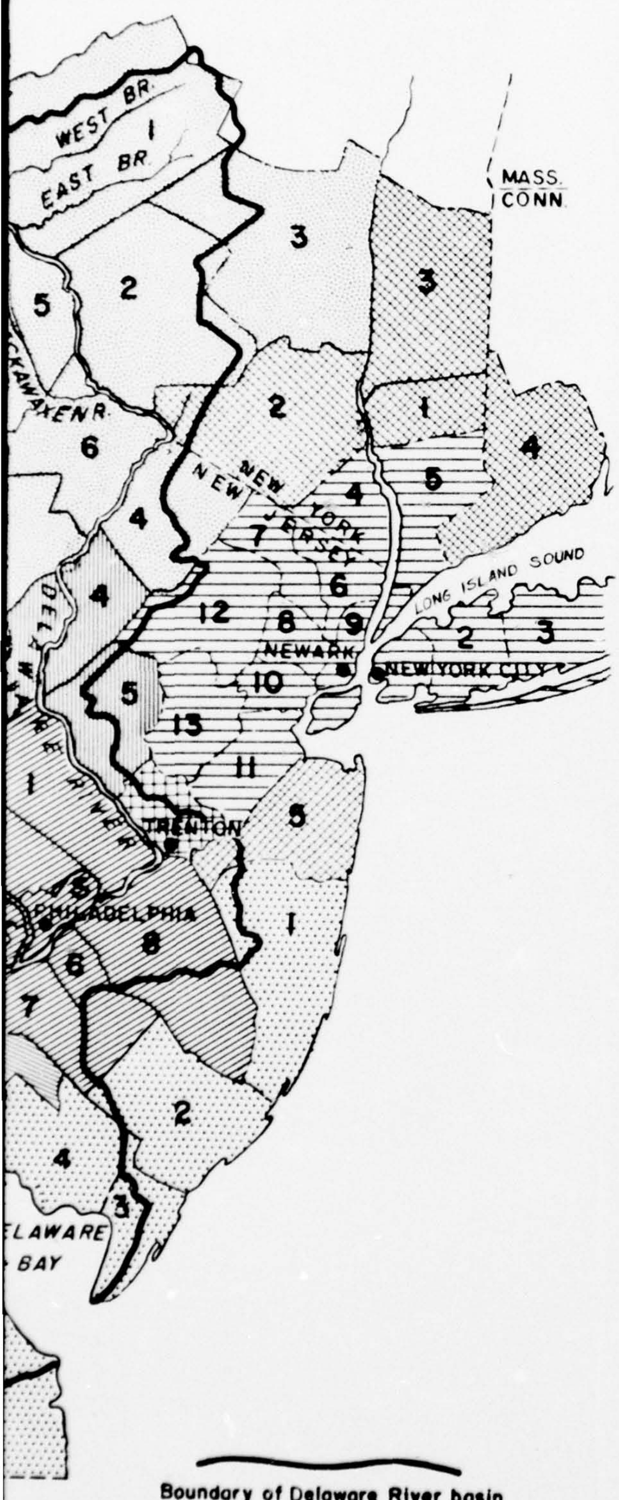
areas. Also ground water is a more important source of supply in the Coastal Plain than in the Appalachian Highlands, northeast of the Fall Line; roughly two-thirds of the ground water pumped in the Delaware River basin is from the unconsolidated deposits of the Coastal Plain, which constitutes only one-fourth the area of the basin.

Because ground-water supplies are but a part of the total it is emphasized here that the magnitude of the potential ground-water supply of the Delaware River service area cannot be evaluated apart from the overall total, as if ground water were a separate resource. Thus, it is axiomatic that heavy development of surface-water supplies tends to limit the amount of perennially recoverable ground water and conversely. In the final analysis, economic and other factors beyond the scope of this report determine the extent to which ground-water supplies are developed. This report attempts to indicate only the physical possibilities for ground-water development in the Delaware River service area.

U. S. GEOLOGICAL SURVEY



GROUPINGS OF COUNTIES IN THE DELAWARE R



EXPLANATION

A.- NEW YORK CITY METROPOLITAN AREA (STANDARD AREA)

NEW YORK	NEW JERSEY	
1. 5 N.Y.C. Boroughs	6. Bergen	10. Union
2. Nassau	7. Passaic	11. Middlesex
3. Suffolk	8. Essex	12. Morris
4. Rockland	9. Hudson	13. Somerset
5. Westchester		

B.- NEW YORK CITY METROPOLITAN AREA (SUPPLEMENT FOR EXPANDED AREA)

NEW YORK	CONNECTICUT	NEW JERSEY
1. Putnam	4. Fairfield	5. Monmouth
2. Orange		
3. Dutchess		

C.- BETHLEHEM-ALLENTOWN AND READING METROPOLITAN AREAS

PENNSYLVANIA		NEW JERSEY
1. Lehigh	3. Berks	4. Warren
2. Northampton		5. Hunterdon

D.- TRENTON METROPOLITAN AREA - NEW JERSEY

1. Mercer

E.- PHILADELPHIA METROPOLITAN AREA

PENNSYLVANIA		NEW JERSEY
1. Bucks	4. Delaware	6. Camden
2. Montgomery	5. Philadelphia	7. Gloucester
3. Chester		8. Burlington

F.- WILMINGTON METROPOLITAN AREA

NEW JERSEY	DELAWARE
1. Salem	2. New Castle

G.- UPPER BASIN AREA

NEW YORK		PENNSYLVANIA
1. Delaware	3. Ulster	5. Wayne
2. Sullivan		6. Pike
		7. Monroe
NEW JERSEY		8. Carbon
4. Sussex		9. Schuylkill

H.- SOUTHERN BASIN AND COASTAL AREA

NEW JERSEY		DELAWARE
1. Ocean	4. Cumberland	5. Kent
2. Atlantic		6. Sussex
3. Cape May		

UPINGS OF COUNTIES IN THE DELAWARE RIVER SERVICE AREA

2

GENERAL GROUND-WATER HYDROLOGY OF THE BASIN

SOURCES OF GROUND WATER

In the Delaware River service area all ground water is derived from precipitation. Under the humid conditions prevailing in the region aquifers are usually full to overflowing and are so maintained by precipitation. When the capacity of the soil to retain water against gravity (the field capacity of the soil) is exceeded, the excess water percolates to the water table to become ground water.

Throughout most of their courses the streams of the service area usually act as drains rather than as sources of water. Seepage from streams therefore contributes recharge to ground water only where pumping of wells near streams reverses the natural direction of ground-water movement toward the streams. Under these circumstances substantial quantities of recharge may be induced from the streams. Near the ocean or other bodies of saline water such a reversal of movement may cause encroachment of the saline water.

OCCURRENCE AND MOVEMENT

Ground water may be considered as the water that is stored temporarily in saturated openings in earth material and that provides the water to wells, springs, and fair-weather flow of streams. A bed or zone of such materials that is capable of yielding usable quantities of water to wells is called an aquifer. Aquifers have two principal functions: they store water and they transmit water.

Storage is perhaps the primary function of aquifers in which the water exists under unconfined, or water-table, conditions. Such conditions are most common near the land surface in permeable materials such as the coarse-grained deposits in large areas in the Coastal Plain and the thick mantle of weathered rock in many parts of the Piedmont physiographic province. Such aquifers obtain recharge directly from rain or snow in their storage areas.

On the other hand, aquifers that contain water under confined, or artesian, conditions serve principally as conduits to transmit water from intake (recharge) areas to discharge areas. Artesian aquifers are enclosed by beds or zones of relatively impermeable materials (aquicludes) which, though they may be saturated, yield little water and act as barriers to water movement. The best examples of aquicludes and artesian aquifers in the basin are the extensive, alternating layers of clay and sand in the Coastal Plain province.

Aquifers in the basin range widely in their capacity to store, transmit, and yield water. Their most significant hydrologic properties are their coefficients of storage, permeability, and transmissibility. Porosity is not so important, because not all, and in some materials such as clay very little, of the water stored in the openings of a material will drain by gravity; hence some of this total storage capacity is not usable.

Coefficient of storage is the volume of water released from or taken into storage by an aquifer per unit surface area per unit change in the component of head (water pressure) perpendicular to that surface. In artesian aquifers, where the withdrawn water comes from elastic adjustment to head changes rather than from drainage of the pores, the storage coefficient is very small, commonly 0.00001 to 0.001, whereas in water-table aquifers, where the material is actually drained, the coefficient of storage commonly ranges from 0.05, and sometimes less, to 0.30.

The coefficient of permeability of a material as used by the U. S. Geological Survey is the rate of flow of water in gallons per day through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot, at a temperature of 60°F. The field coefficient of permeability is the same except that it is measured at the prevailing water temperature rather than at 60°F. Some of the deposits of coarse sand and gravel have permeability coefficients exceeding 3,000 gpd per square foot, whereas most beds of clay have permeability coefficients of a very small fraction of 1 gpd per square foot.

The coefficient of transmissibility may be regarded as the product of the average field permeability of an aquifer and its thickness; it is expressed in gallons per day per foot. It indicates the capacity of the aquifer, as a unit, to transmit water at the prevailing temperature, under any given hydraulic gradient. Transmissibility coefficients greater than 100,000 gpd per foot have been measured for sand aquifers in the Coastal Plain, but coefficients less than 1 gpd per foot have been estimated for adjacent clay aquicludes.

Ground water, like surface water, moves in the direction of decreasing hydraulic head. In water-table aquifers the water moves in fairly direct paths from higher to lower areas in the outcrop, but in artesian aquifers the water may follow long and sometimes rather circuitous paths. In the Delaware River service area distances traveled from intake points to discharge points in water-table aquifers range from only a few feet to thousands of feet. In artesian aquifers, such as those of the Coastal Plain, distances traveled by some of the water from the recharge at the outcrop to discharge points range from a few miles to tens of miles; however, some artesian recharge is obtained from leakage through confining beds; therefore, recharge from such sources may be in the order of a few tens to several hundreds of feet. Times of transit also range widely from a few hours or days to tens and even hundreds of thousands of years.

DISCHARGE

Natural discharge of ground water takes place where the top of the saturated zone--the water table, or the overlying capillary fringe--is at or near the land surface. Some of this water returns to the atmosphere by the processes of evapotranspiration and thus may be considered as part of the natural loss. The remainder enters streams or other bodies of surface water and becomes a part of the water crop.

In addition to natural discharge, considerable quantities of water are in places discharged artificially by pumped wells, mines, and quarries. New patterns of ground-water movement toward the pumped areas become established, and discharge at natural outlets may diminish or cease.

In the basin most natural ground-water discharge occurs at relatively low parts of the outcrop of aquifers--along streams, in wet or swampy areas, and into the bays, estuaries, or ocean. The total amount of such natural discharge, including evapotranspiration, is not accurately known; however, it is estimated that about half the average annual streamflow in the basin is supplied from ground-water discharge. The total pumpage from basin aquifers is estimated to be about 340 mgd and the total ground-water discharge to streams is estimated to be about 6,000 mgd; in addition, an unknown quantity bypasses the streams and leaves the basin mainly in the Coastal Plain aquifers. Therefore, the ground-water pumpage is probably 5 percent or less of the total; certainly it is less than 10 percent.

TYPES OF AQUIFERS

Based on the nature of their water-bearing openings, two major types of aquifers exist within the Delaware River service area, those consisting of unconsolidated sediments and those consisting of consolidated rocks,(pl. 2).

Unconsolidated sediments consist of loose granular materials, deposited by water, wind, or ice, in which essentially all the water-bearing openings are pores between the grains. Laboratory-determined porosities of sand samples from the Coastal Plain in New Jersey range from about 25 to 45 percent (Barksdale, Greenman, Lang, and others, 1958), and some clays have even higher porosities.

Not all the water stored in the pores will drain by gravity, however. The term specific yield is therefore used to indicate the ratio of the volume of water that can drain by gravity from a saturated material to the volume of the material. This ratio, like porosity, usually is expressed as a percentage. Where free drainage occurs, as under water-table (unconfined) conditions, the specific yield is practically equal to the coefficient of storage.

In many parts of the Delaware River service area the specific yield of sand and gravel exceeds 25 percent. However, in clay and silt most of the water is retained in the tiny pores by molecular forces (capillary attraction), and the specific yield may approach zero.

Consolidated rocks are dense, coherent materials which, in their fresh, unweathered state, have little or no intergranular porosity. Instead, the water-bearing openings consist largely of fractures, some of which are solutionally enlarged. Where weathered, such rocks may resemble unconsolidated sediments in having intergranular pores, and the distinction between the two types is not sharp.

In the service area the consolidated rocks comprise three principal categories, each having distinct water-bearing properties: clastic rocks; carbonate rocks; and crystalline rocks.

Clastic rocks include shale, sandstone, conglomerate, and related rocks, all of which were deposited originally as unconsolidated sediments. These materials have been hardened by cementation or compaction so that little remains of their original intergranular porosity, and most of their water occurs in fractures. However, some sandstone and conglomerate contain significant amounts of water in their intergranular pores where the cementing material has been dissolved.

Carbonate rocks, also of sedimentary origin, include limestone (calcium carbonate), dolomite (calcium and magnesium carbonate), dolomitic limestone, and rocks gradational between the pure carbonate rocks and the clastic rocks in which the carbonate content is substantial. Carbonate rocks differ from other categories chiefly in having solution channels or cavities in addition to the other types of openings. Although the aggregate volume of the solution openings usually is but a small percentage of the total volume

2A

Outcrop of black shale (Marcellus shale of Devonian age) at Wallace St. and Fulmer Ave., Stroudsburg, Pa. Here the "shale" is more nearly a claystone. Although numerous fractures occur in the claystone, the fractures are tight and water can move through them only very slowly. Wells developed in such bedrock would have very low yields.

2B

Kame-terrace deposit at Hawley, Pa. Such sandy and gravelly materials of glacial melt-water origin are highly permeable and where saturated, yield large quantities of water to wells.

Plate 2.--Photographs of geologic rock materials of contrasting hydrologic properties, Delaware River basin area

of rock, their relatively large size permits rapid movement of water, and the permeability of some carbonate rocks in the basin area compares favorably with that of the coarse-grained unconsolidated sediments.

Crystalline rocks, which are composed of interlocking mineral grains (crystals) have virtually no intergranular porosity, except where altered by weathering. Fractures in these rocks commonly contain small but significant quantities of water; however, in the area of this report few such openings extend deeper than about 300 feet, and most of the water is contained at much shallower depths. Considerable quantities of water occur in thick zones of weathered crystalline rocks such as are found in the Piedmont upland (pl 3).

The consolidated-rock aquifers, as a group, are markedly inferior in their capacity to store and transmit and yield water. Probably few consolidated rocks have a specific yield as great as 2 percent, in contrast to the specific yields of 20 percent or more common in sand and gravel. Coefficients of transmissibility of 50,000 — 150,000 gpd per foot have been measured in several unconsolidated granular aquifers (tables 3 and 4), but, with the exception of some of the carbonate-rock aquifers and possibly some of the coarse-grained sandstone and conglomerate aquifers, probably few consolidated-rock aquifers have coefficients of transmissibility higher than 5,000 gpd per foot.

HYDROLOGIC PROVINCES

The Delaware River basin comprises 2 greatly different hydrologic provinces which correspond to the 2 major physiographic units in the region: the Atlantic Plain occupying approximately the southern fourth of the basin; and the Appalachian Highlands constituting the northern three-fourths of the basin (pl. 2). The 2 provinces are separated by the Fall Line, which extends northeasterly across the southern part of the basin and lies along the northwest side of the Delaware River between Wilmington, Del., and Trenton, N. J.

The Atlantic Plain, or Coastal Plain as its emerged part is designated, is underlain by a wedge of unconsolidated sediments having its northwestern edge along the Fall Line. This great wedge thickens seaward, reaching a maximum thickness of about 6,000 feet beneath the mouth of Delaware Bay (pl. 4). It consists of an alternating sequence of sheet-like layers of sand, clay, and some gravel. Enormous quantities of water are stored in this great mass of deposits, and its aquifers transmit water much more readily than most of the consolidated-rock aquifers of the Appalachian Highlands.

In contrast, the Appalachian Highlands are underlain predominantly by consolidated rocks. In general, the consolidated-rock aquifers store and transmit much less water than the unconsolidated granular aquifers of the Coastal Plain. Unconsolidated deposits of glacial origin discontinuously mantle the northern part of the Highlands and occur also as tongue-shaped valley fills of glacial outwash throughout both northern and southern parts. Although the aggregate amount of water stored in the outwash is small compared with that in the consolidated rocks, the supplies from these deposits are readily available to wells and, under favorable conditions, may be augmented considerably by recharge induced from hydraulically connected streams and lakes.

The Appalachian Highlands include 4 physiographic provinces, each of which has distinctive landforms resulting from the types and structure of the underlying rocks and the geologic history of the region. From the Fall Line northward these physiographic provinces, as classified by Fenneman (1938), comprise the Piedmont, New England, Valley and Ridge, and Appalachian Plateaus provinces (pl. 3). The characteristics of each province and its subdivisions are described briefly farther on in the discussion of the Appalachian Highlands part of the basin.

THE COASTAL PLAIN

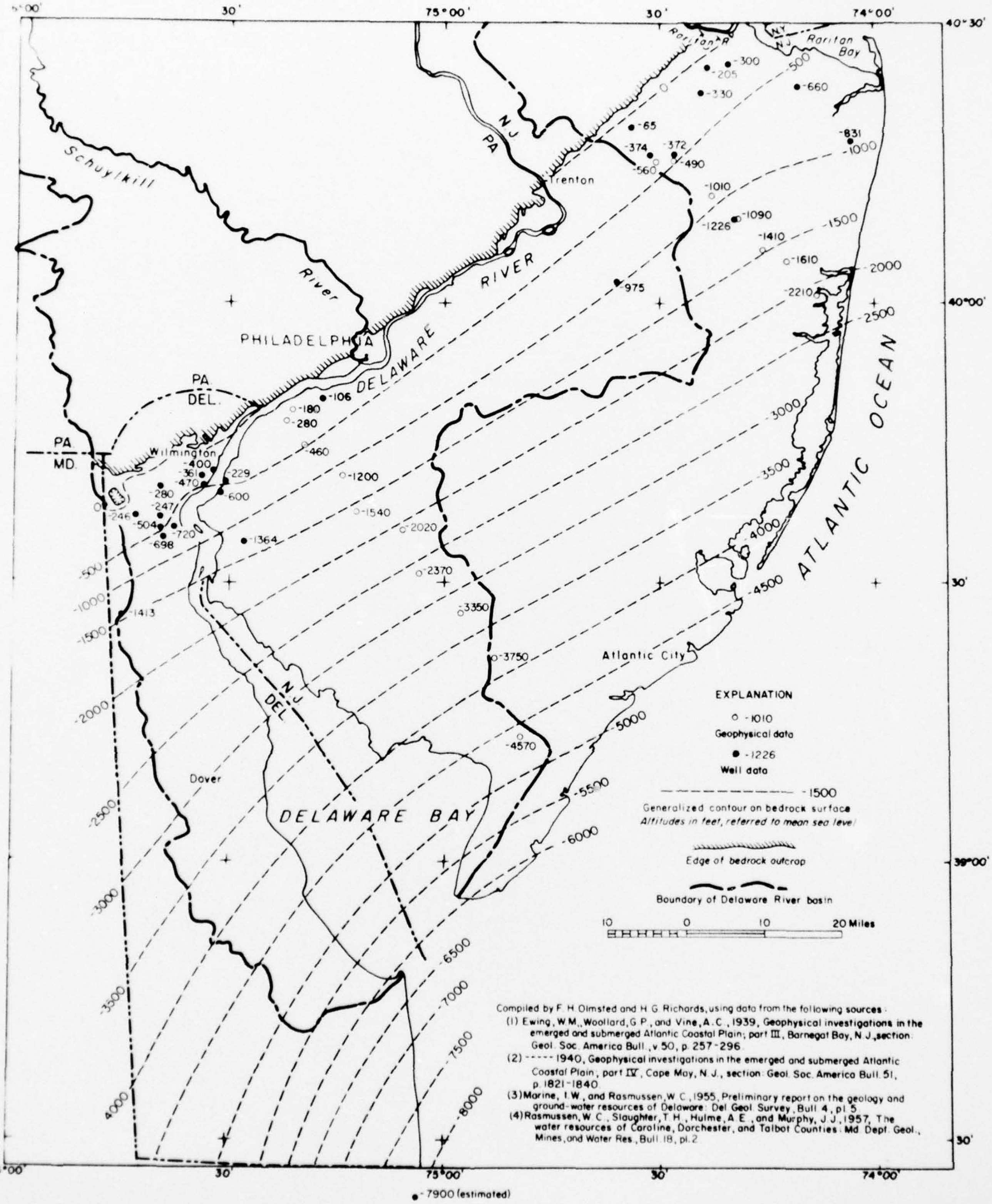
GENERAL FEATURES

The Coastal Plain physiographic province is the emerged part of the Atlantic Plain (pl. 3), a gently sloping surface that extends 125-175 miles southeasterly from the Fall Line beyond the present coastline to the edge of the continental shelf. A net rise of sea level in the last 10,000 years since the shrinkage and disappearance of the continental glaciers of the most recent ice age (Wisconsin age) has inundated the outer part of the Atlantic Plain and has "drowned" the lower reaches of the streams, forming bays, estuaries, and tidal marshes near their mouths. Delaware Bay and the estuary of the Delaware River, which extends inland 133 miles from the mouth of the Bay to the Fall Line at Trenton, N. J., has been formed by this sea-level rise, which has amounted to about 150 feet (Flint, 1957, p. 262).

The Coastal Plain occupies the south half of New Jersey, most of Delaware, and a narrow strip in southeastern Pennsylvania along the northwest side of the Delaware River. Excluding tidal marshes and bays, it includes an area of about 2,750 square miles within the basin and about 2,150 square miles in coastal New Jersey outside the basin. In width it decreases toward the northeast from about 70 miles in Delaware to less than 20 miles at Raritan Bay in New Jersey. Long Island, N. Y., averaging about 16 miles in width, is the continuation of the Coastal Plain in that State.

U.S. GEOLOGICAL SURVEY

PLATE 4



CONFIGURATION OF BEDROCK BENEATH COASTAL PLAIN OF DELAWARE RIVER BASIN AND ADJACENT DELAWARE AND NEW JERSEY

Throughout most of New Jersey the Coastal Plain consists of an inner part which slopes gently northwest toward the Delaware and Raritan Rivers and an outer part which slopes even more gently southeast toward the ocean, or, in the southern end of the State, south and southwest toward the Delaware Bay. In Delaware, the plain slopes east toward the Delaware River and Bay.

The land surface is nearly flat over wide areas but is moderately hilly in places, particularly toward the northeast, in the vicinity of Raritan Bay. In that area a few hilltops rise to nearly 400 feet above sea level, but in general altitudes greater than 200 feet are rare, and more than half of the plain is below an altitude of 100 feet.

The inner, northwestern part of the Coastal Plain in New Jersey is crossed by a sequence of approximately parallel belts, which are the beveled edges or outcrops of the geologic formations that dip toward the ocean (pls. 5 and 6). Where outcrops are not mantled by younger deposits of sand and gravel, each belt has a distinctive landform resulting from the relative resistance to erosion of the underlying materials. Unusually resistant beds such as sandstone or conglomerate (cemented sand or gravel) form steep-sided hills and ridges; beds of clay tend to form broad interstream surfaces but steep stream banks; and loose sand beds form gentle valley sides, or where wind action is strong and the sand is not held in place by vegetation, dunes and "blowouts" may be formed. In plan view, some of the outcrop belts are deeply frayed or indented where they are crossed by the small streams flowing toward the Delaware or Raritan Rivers (pl. 6). Below the bend at Trenton, N. J., the Delaware River follows the innermost belt--the largely concealed beveled edge--of the basal unit consisting of nonmarine sediments of Cretaceous age. The relative weakness of these materials and the resistance to erosion of the hard crystalline rocks immediately to the northwest across the Fall Line have evidently determined the course of this part of the river.

The outer margin of the Coastal Plain in New Jersey has very low relief and slopes gently toward the ocean on the east and southeast, and toward the bay on the south. In Delaware the topography is similar, except that the prevailing slope and drainage is toward the east. These areas are immediately underlain for the most part by permeable sand and gravel and are traversed by perennial streams of low gradient. In their shoreward reaches most of the streams are tidal and are bordered by marshes. The coast in central and southern New Jersey is characterized by a line of offshore sand bars, formed by longshore currents and wave action, behind which lie shallow bays and marshes. Atlantic City is built on one of these bars.

The deposits underlying the Coastal Plain form a wedge which consists of an alternating sequence of relatively permeable coarse-grained beds of sand and gravel and relatively impermeable fine-grained layers of clay and silt. The coarse-grained beds and the fine-grained beds constitute, respectively, aquifers and aquicludes of variable thickness and extent. These aquifers and aquicludes correspond in a general way to the geologic formations that have been established on the basis of both physical character and age as determined from fossils. However, the boundaries of the aquifers and aquicludes are not everywhere the same as those of the formations, because the formations change in character from place to place--a formation may be predominantly coarse-grained and classed as an aquifer at one place, and predominantly fine-grained and classed as an aquiclude at another--, and because some of the formations comprise several aquifers and aquicludes, and because aquifers in two adjacent formations may join to form a single hydrologic unit.

The geologic formations that comprise the unconsolidated sediments of the Coastal Plain are listed in the order of their age on pages 15, 16, and are described briefly in table 1. The sequence lies on a platform of the consolidated rocks of the same type as are exposed northwest of the Fall Line. This platform, which had been eroded to a surface of very low to moderate relief by the beginning of the Cretaceous period, about 125 million years ago (table 1), now slopes southeastward from the Fall Line, where it is slightly above sea level, toward the ocean, where it is about 6,000 feet below sea level at the mouth of Delaware Bay--an average slope of about 83 feet per mile. Plate 4 shows the configuration of this surface in a very general way; not enough deep-well information and geophysical data are available to determine the buried topography in detail.

Nearly all the formations in the overlying wedge of deposits thicken seaward. Dips of the formations therefore decrease upward in the sequence from about 75 to 80 feet per mile in the Cretaceous formations near the base to perhaps only slightly more than the slope of the outer part of the Coastal Plain--about 10 feet per mile in the Cohansey sand --near the top of the sequence.

Besides thickening seaward, most of the formations become finer grained and more difficult to identify in that direction. Oscillations of the ancient shoreline caused the deposition of materials in alternating layers of different character that allows classification of the deposits into formations toward the northwest in and near their outcrop. However, because the ocean lay to the east throughout the time that all the deposits were accumulating, just as it does at present, all the formations probably grade eastward and southeastward into fine-grained silt and clay of deep-water origin, and it is believed unlikely that many beds of sand extend as far as the edge of the continental shelf, some 100 miles east of the present shoreline.

Nevertheless, some of the sandy aquifers probably extend at least several miles beyond the present shoreline. Some of these aquifers were deposited in the ocean and therefore were originally saturated with salt water. Now, however, they contain fresh water, which indicates that infiltrating precipitation has filled the inland recharge areas of the aquifers, moved through them to the sea and in doing so has flushed the salt water out. This implies, of course, a connection between sea and land through the aquifers and has an important bearing on problems of salt-water encroachment along the coast.

Bearing in mind that most of the formations change in character from place to place and may be missing altogether at some localities, a generalized picture of the sequence of aquifers and aquicludes is provided by the following list. The age increases toward the bottom of the list; hence in general, the units are in the order they would be penetrated in a well.

Beach and dune sand	A minor aquifer
Marsh and swamp deposits	A portal for recharge and discharge
Alluvium and glacial outwash	An aquifer, more important in Appalachian Highlands than elsewhere
Basin-rim sand	A portal for recharge and discharge
Talbot and Cape May formations	An aquifer and portal for recharge and discharge
Unclassified deposits Pensauken formation Bridgeton formation	A portal for recharge and locally a minor aquifer
Beacon Hill gravel	An entry for recharge
Cohansey sand	A major water-table aquifer
Kirkwood formation	A significant group of aquifers and aquicludes
Piney Point formation	An entirely confined aquifer in southern part of basin
Shark River marl Manasquan marl	A minor imperfect aquiclude
Vincentown sand	A minor aquifer
Hornerstown marl	Together with Navesink marl, an imperfect aquiclude
Red Bank sand	An aquifer in northeastern part of area, largely outside basin
Navesink marl	Together with Hornerstown marl, an imperfect aquiclude
Mount Laurel sand Wenonah sand	An extensive minor aquifer. In Delaware, Mount Laurel sand not distinguished from Navesink marl

Marshalltown formation	An imperfect aquiclude; not known in Delaware
Englishtown sand	A highly variable minor aquifer; not present in Delaware
Woodbury clay, Merchantville clay	An extensive major aquiclude
Nonmarine sediments: Magothy formation, Raritan formation, Patapsco formation, Patuxent formation	A complex group of aquifers and aquicludes. Aquifers constitute most important present source of ground water in basin

OCCURRENCE OF GROUND WATER

Very large quantities of fresh water occur in the great wedge of unconsolidated sediments underlying the Coastal Plain. Nearly all the usable water--that is, the water that can be withdrawn by wells--is in sheetlike layers of sand and lenslike beds of sand and gravel. These layers of sand and gravel--the aquifers--are interbedded with aquicludes composed of silt and clay which restrict the movement of water and confine the water in some of the aquifers under artesian pressure. The aquicludes generally increase in thickness and relative abundance toward the coast, reflecting the seaward change to a deeper water origin of the deposits.

Fresh water occurs, or occurred under native conditions, in all the near-surface materials in the Coastal Plain; however, salt water is contained in the lower, seaward part of the wedge in accordance with the Ghyben-Herzberg principle (p. 54).

The inland extent of the salty ground water is different in each aquifer. In general, the salt water extends farthest inland in the lowest aquifers. The aquifers in the nonmarine sediments of Cretaceous age contain salt water as far inland as 50 miles. At Atlantic City, N. J., the "800-foot" sand aquifer in the Kirkwood formation still contains fresh water, despite pumping which has lowered the fresh-water head in the aquifer by more than 100 feet (Barksdale, Greenman, Lang, and others, 1958), but the aquifers below the Kirkwood formation in this area contain only salty water. Salty water occurs in shallow aquifers of both the Cohansey sand and the Quaternary deposits at places along the coast, but this probably has resulted largely from pumping and to a lesser extent from dredging and draining activities; it is not a natural condition.

The outcrops or intake areas of the aquifers in the Coastal Plain are shown on plates 6 and 7. The Quaternary deposits (pl. 7), which blanket large areas of the older aquifers, covering practically all of Delaware and much of southern New Jersey, contain unconfined to semiconfined water and function somewhat as a sponge to receive infiltration from precipitation and transmit it to the underlying aquifers.

Plate 8 is an idealized cross section showing geologic and hydrologic conditions in a Coastal Plain setting similar to that of New Jersey or Delaware. A capping layer of permeable sand and gravel lies unconformably over the seaward-dipping pre-Quaternary deposits that constitute a system of aquifers and aquicludes. The Quaternary capping layer itself is largely an unconfined aquifer. Its water table is a subdued replica of the land surface and water flows from high to low areas. The recharge that does not escape locally to streams--some of it soon enough to be considered a part of the direct runoff, but most of it as base flow--direct runoff, or to the atmosphere through evapotranspiration is available to underlying aquifers (designated A, B, and C in the diagram) through the so-called "funnel effect." This is a system by means of which precipitation collected over a fairly extensive area of land surface is made available as recharge to smaller underlying permeable zones--the subsurface intake areas of the older aquifers.

Plate 8 illustrates also how parts of an aquifer can be both artesian and nonartesian, although the case is necessarily greatly oversimplified.

The older aquifers (pl. 6) also contain unconfined water in much of their outcrop or where covered by the Quaternary deposits, although semiconfinement occurs where lenses of silt and clay inhibit the movement of water between the water table and deeper parts of the aquifers. As may be inferred from subsurface data on the character of the materials and from the results of pumping tests, complete lack of confinement, or true water-table conditions, probably are rather uncommon even in the shallower aquifers of the Coastal Plain, and conditions approaching true confinement exist in most of the nonmarine sediments of Cretaceous age which contain numerous lenticular bodies of clay and silt that greatly restrict vertical movement of water. Nevertheless, during extensive periods of withdrawal and recharge of water, essentially unconfined conditions exist in the outcrop areas of most of the Coastal Plain aquifers.

Down the dip, toward the coast, water in the aquifers below the Cohansey sand is confined by the intervening aquicludes. Under natural conditions interchange of water through the aquicludes is extremely slow and probably minor in amount. However, significant

quantities of water may move through an aquiclude where a large difference in hydraulic head between the adjacent aquifers is created by pumping from one aquifer. For example, assume the following conditions: thickness of aquiclude is 100 feet; average coefficient of permeability of aquiclude is 0.01 gpd per square foot; and difference in head between adjacent aquifers is 50 feet. Then, the quantity of water moving through a square-mile area of the aquiclude would be about 140,000 gpd--an amount sufficient to supply a town of 1,000 people at an average rate of consumption of 140 gpd per person.

The physical and hydrologic properties of the aquifers and aquicludes of the Coastal Plain are described briefly in order from oldest to youngest in the following pages; and a more abbreviated description is provided in table 1 . Later sections summarize the movement of ground water through the Coastal Plain deposits, the importance of storage, the chemical character of the ground-water supplies, the problems of present and potential salt-water encroachment, and the productivity of the aquifers.

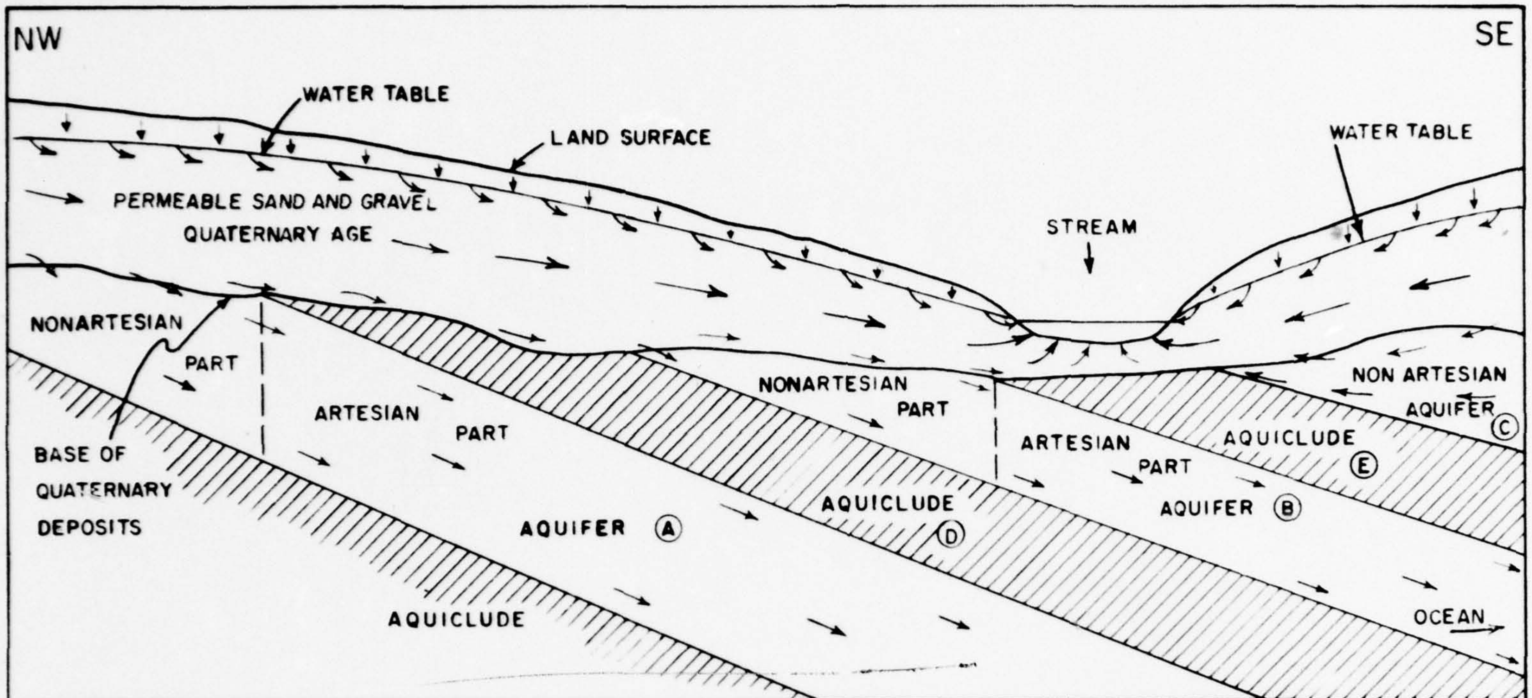
Nonmarine Sediments of Cretaceous Age--the Major Group of Aquifers

The nonmarine sediments of Cretaceous age include in ascending order the Patuxent, Patapsco, Raritan, and Magothy formations (table 1). These formations are not separated herein, because together they constitute a major hydrologic unit whose individual aquifers and aquicludes are comparatively inextensive and therefore susceptible of classification only in restricted areas.

The nonmarine sediments--the lowermost part of the unconsolidated sediments in the Coastal Plain--form a seaward-thickening wedge that lies on a surface of low relief cut on consolidated rocks similar to those which crop out northwest of the Fall Line (pls. 4 and 5). The wedge thickens southeastward from zero along the Fall Line to more than 3,500 feet beneath the mouth of Delaware Bay and more than 5,000 feet beneath the southeastern corner of Delaware. The beveled northwestern edge of the nonmarine sediments, most of which is not an outcrop but is largely covered with Quaternary deposits (compare pls. 6 and 7) forms a lowland that extends from northern Delaware 100 miles to the lower Raritan River and Raritan Bay in northeastern New Jersey. Much of the Delaware River estuary lies along this belt, as does the Raritan River and its southwestern tributaries. Largely because of their location near the Fall Line where the large centers of population and industry are concentrated, the aquifers in the nonmarine sediments are more completely developed and provide more water supplies than any of the other aquifers in the basin.

U. S. GEOLOGICAL SURVEY

PLATE 8



NOTE: Vertical scale greatly exaggerated, hence dip of pre-Quaternary aquifers and aquicludes is more nearly horizontal. Paths of ground-water movement, indicated by arrows, likewise are not to scale; vertical components of movement are greatly exaggerated. (components of movement perpendicular to diagram are not indicated)

IDEALIZED CROSS SECTION ILLUSTRATING "FUNNEL EFFECT" IN RECHARGE TO COASTAL-PLAIN AQUIFERS

The sediments represent several nonmarine environments--stream, marsh, lagoonal, and estuarine--and, in the upper part, there are thin tongues of marine deposits. The individual beds or layers, which are much less extensive than the beds in the overlying formations of marine origin, consist of sand, clay, silt, and a little gravel. Varicolored tough clay and light, cross-bedded, fine- to coarse-grained sand are typical. Lignite (a brown low-grade coal) and pyrite (an iron-sulfide mineral) are prominent in some places. A few thin limy beds containing shells occur in the seaward part of the sequence.

The hydrologic properties of the nonmarine sediments vary greatly. Some of the layers of coarse-grained sand are highly permeable, but many of the intervening layers of clay are nearly impermeable. Laboratory coefficients of permeability for samples from the Raritan formation in Middlesex County, N. J., ranged from 25 to 3,500 gpd per square foot and gave a weighted average of about 1,300 gpd per square foot; the average coefficient for sands in the Magothy formation was about 400 gpd per square foot (Barksdale, and others, 1943).

Pumping tests in New Jersey gave permeability coefficients ranging from 240 to 2,500 gpd per square foot and averaging about 1,200 gpd per square foot, although the results of 2 tests in northern Delaware indicated lower permeabilities there (table 2).

Coefficients of transmissibility from 14 pumping tests in New Jersey, Delaware, and Pennsylvania (table 2) ranged from 5,000 to 150,000 gpd per foot and averaged 60,000 gpd per foot. None of these values is based on a penetration of the entire thickness of the nonmarine sediments; the thickness of aquifers tapped ranged from 10 to 100 feet, and even the 100-foot thickness represented only partial penetration of the unit.

In contrast to the moderate to high permeability and transmissibility of the aquifers in the nonmarine sediments, the clay aquicludes probably have permeability coefficients of less than 0.1 gpd per square foot. One aquiclude in the vicinity of Camden, N. J., has an estimated coefficient of transmissibility of about 0.4 gpd per foot (Barksdale, Greenman, Lang, and others, 1958).

Specific yields, determined by the Geological Survey's Hydrologic Laboratory, of samples of sand from Middlesex County, N. J., averaged about 35 percent for the Raritan formation and about 40 percent for the Magothy formation. Coefficients of storage determined from the pumping tests listed in table 4 ranged from .000062 to .0016 -- indicative of confined conditions--and the median was about .0003.

Table 2.--Coefficients of transmissibility, permeability, and storage in nonmarine sediments of Cretaceous age

Location	Coefficient of transmissibility (gpd/ft) Range	Coefficient of transmissibility (gpd/ft) Midpoint between extremes	Thickness of aquifer (ft)	Coefficient of permeability (gpd/sq ft) Range	Coefficient of permeability (gpd/sq ft) Midpoint between extremes	Coefficient of storage (dimensionless) Range	Coefficient of storage (dimensionless) Midpoint between extremes	Source of data
Riverton, N. J.	-	150,000 1/	100 1/	-	1,500 1/	-	0.00015	USGS unpubl. data
Woodbridge, N. J.	4,000-14,000	9,000	10-24	240- 660	450	0.00004 -0.081	0.0006 2/	do
Camden, N. J. (central)	23,000-79,000	51,000	19-46	680-2,500	1,600	.00017 - .00056	.00037	USGS; Leggette & Brashears unpubl. data
Gibbstown, N.J.	-	47,000	25±	-	1,500	-	.00015	USGS unpubl. data
Haddon Heights, N.J.	-	120,000	70±	-	1,800	-	.0010	do
Camden, N. J. (Stockton sta.)	53,000-64,000	58,000	45-50	1,100-1,400	1,200	.000072- .000086	.000079	do
Camden, N. J. (south)	-	62,000 1/	24 1/	-	2,600 1/	-	.0012	do
Parlin, N. J. (DuPont)	50,000-76,000	63,000	85	590- 890	740	.000037- .000086	.000062	do
Parlin, N. J. (Hercules)	-	100,000	66	-	1,500	-	.0016	do
Old Bridge, N. J.	17,000-67,000	42,000	-	-	-	.00058 - .0024	.0015 2/	do
Westville, N.J.	51,000-68,000	60,000	40-67	1,000-1,400	1,200	.000090- .00017	.0001	do
Philadelphia, Pa. (Navy Yard)	51,000-69,000	60,000	54-63	920-1,200	1,100	.000080- .00020	.00014	USGS open-file memo Graham & Kammerer
Delaware City, Del.	2,500- 7,500 3/	5,000 3/	-	-	-	.00006 - .0015	.0005 2/	industrial consultant
Northern Delaware	4,700-11,000	8,000	-	-	-	.0001 - .0003	.0002	do

1/ Aquifer probably was not fully penetrated
2/ Assumed average
3/ Rational values estimated from map showing lines of equal coefficient of transmissibility

In New Jersey, most wells in the nonmarine sediments that are designed for large capacity, yield in the range of 300 to 1,000 gpm, and yields exceeding 1,000 gpm are not uncommon. In Delaware, yields are considerably less, as a rule. Rasmussen and others (1957, table 15) reported an average specific capacity (discharge of a pumping well divided by the drawdown of water level) of only about 2 gpm per foot of drawdown for 66 wells in northern Delaware. This value indicates an average coefficient of transmissibility in the order of only 4,000 or 5,000 gpd per foot which is comparable with the 2,500-8,000 gpd per foot values derived from pumping tests at 2 sites in that area (table 2).

Although individual beds of sand and clay in the nonmarine sediments are quite lenticular, water-yielding zones have been recognized in the most intensively studied areas. These zones appear to be separated by layers of clay that are more extensive than those separating the individual sandy layers within each zone, and definite differences in artesian pressure and also in the chemical character of the contained water exist between the zones. In northern Delaware Rasmussen and others (1957) defined 3 zones which were called the lower, middle, and upper aquifers; in the Philadelphia-Camden area, 2 principal zones appear to be present. Graham (1950, p. 214-16, fig. 3) has given a lucid and concise description of the ground-water occurrence in the Philadelphia-Camden area, and his geologic cross section illustrates the nature of the 2 zones mentioned above.

Merchantville and Woodbury Clays - a Major Aquiclude

The Merchantville clay and the overlying Woodbury clay together form a widespread major aquiclude confining the water in the nonmarine sediments. The combined unit crops out or is covered by Quaternary deposits in a belt 1 to 4 miles wide lying immediately southeast of the intake area of the nonmarine sediments. Southeast of its outcrop the unit underlies all the Coastal Plain. The Woodbury clay has not been recognized in northern Delaware, but the Merchantville clay there probably is equivalent to the combined Merchantville and Woodbury clays, and possibly also to the Marshalltown formation of New Jersey (Rasmussen and others, 1957, p. 116). Near the outcrop the Merchantville and Woodbury clays together range in thickness from about 100 to 140 feet, but they thicken downdip and attain a maximum known thickness of more than 250 feet in the seaward part of Ocean County, N. J.

The Merchantville clay is a black or greenish-black glauconitic, micaceous clay. Glauconite is a greenish to black amorphous mineral of the iron-potassium-silicate family and has pronounced cation exchange properties; it is commercially mined in parts of New Jersey for use as a water-softening agent. The Merchantville clay is generally greasy and massive, although the upper part is somewhat sandy and in places is distinctly laminated, particularly in Delaware.

The Woodbury clay, on the other hand, is not glauconitic, and consists of a black or bluish-black, somewhat micaceous, tough clay. It weathers to light brown and breaks into distinctive blocks having curved or shell-shaped fractures.

The Merchantville and Woodbury clays, which form the most extensive and impermeable aquiclude in the Coastal Plain, are important chiefly in protecting the underlying aquifers in the nonmarine sediments from contamination or encroachment of salt water from above and in restricting the loss of water from those aquifers by upward leakage. However, even though their permeability is very low, the Merchantville and Woodbury clays are capable of transmitting significant quantities of water where sizable differences in head exist between the overlying and underlying aquifers.

A few wells tap the sandy phases of the Merchantville clay, but the Woodbury clay is everywhere too impermeable to be a source of supply.

Minor Aquifers and Aquicludes Above the Merchantville and Woodbury Clays

Between the aquiclude formed by the Merchantville and Woodbury clays and the Kirkwood formation is a sequence of aquifers and aquicludes ranging in thickness from about 400 feet in its northwestern part to about 1,000 feet beneath the coast at Atlantic City, N. J. None of the aquifers in this sequence is an important source of water supply within the Delaware River basin, although 2 of them--the Englishtown sand and the Red Bank sand--are important outside the basin in the northeastern part of the Coastal Plain. However, all are capable of being used to a considerably greater extent than at present, should the need arise and economic factors be favorable.

Englishtown Sand

Overlying the aquiclude formed by the Merchantville and Woodbury clays in the central and northern parts of the Coastal Plain is the Englishtown sand, a minor aquifer in the basin but a fairly important source of water supply northeast of the basin in Monmouth and Ocean Counties, N. J.

The Englishtown consists of fine-grained to pebbly quartz sand and a few inextensive layers of silt and clay. The sand contains small amounts of mica and glauconite, and in places, some lignite. Locally it is cemented by iron oxide. In outcrop the sand is white, yellow, or brown, but in subsurface it is light gray. Clay and silt, which are not generally abundant, occur mostly in the upper part of the formation.

The Englishtown sand becomes finer grained toward the south and east and thins southward. Its maximum thickness is about 160 feet in Ocean County, N. J., but it wedges out and is missing southwest of Swedesboro, N. J.

The sand beds probably are moderately to highly permeable, whereas the few layers of silt and clay are relatively impermeable. No data on any of the hydraulic coefficients are available, nor have detailed data on productivity of wells been assembled. However, because of the wide range in thickness of the aquifer, its productivity varies greatly from place to place. Within the basin the maximum reported yield per well is 200 gpm, but more probably could be obtained in some places, particularly in the northeastern part of the Coastal Plain, outside the basin.

Marshalltown Formation

The Marshalltown formation is an imperfect aquiclude. It overlies the Englishtown sand in most of the Coastal Plain in New Jersey but overlies the Woodbury clay in Salem County, N. J. In Delaware the Marshalltown has not been recognized, but possibly equivalent beds there have been assigned to the Merchantville clay (Rasmussen and others, 1957, p. 117).

The Marshalltown formation consists of greenish-black to black sandy clay and lenticular beds of glauconitic sand. Downdip to the southeast where the beds of sand become more abundant, the Marshalltown resembles the Englishtown sand and the Wenonah sand. The maximum thickness of the Marshalltown in New Jersey is about 125 feet.

Because it is thin and contains some slightly to moderately permeable beds, the Marshalltown formation constitutes a "leaky" or imperfect aquiclude. Down the dip, where it becomes more sandy, it functions even less effectively as an aquiclude and water moves between the underlying Englishtown sand and the overlying Wenonah sand where the required hydraulic gradients exist (Barksdale, Greenman, Lang, and others, 1958). Domestic supplies of water may be obtained from the Marshalltown at many places, and the sandy parts yield as much as 40 gpm to drilled wells.

Wenonah and Mount Laurel Sands

Throughout most of the Coastal Plain the Wenonah sand and the overlying Mount Laurel sand together form a minor aquifer. In northern Delaware, however, the Mount Laurel sand has been grouped, instead, with the overlying Navesink marl which it resembles there (Rasmussen and others, 1957, p. 118).

The Wenonah sand is a slightly glauconitic, micaceous quartz sand containing local thin layers of silt and clay. The sand is mostly fine- to medium-grained and gray or black where unweathered, although in outcrop it is generally white, yellow, brown, or red. In northern Delaware it grades downward into the Merchantville clay.

The overlying Mount Laurel sand contains more glauconite than does the Wenonah sand, is salt-and-pepper-colored, and is mostly medium to coarse-grained, though in northern Delaware it is finer grained and contains considerable amounts of silt and clay. In places the Mount Laurel is cemented by iron oxide to form a brown sandstone.

The outcrop of the Wenonah and Mount Laurel sands forms an irregular belt $\frac{1}{2}$ mile to 3 miles wide across the northeast part of the Coastal Plain about 8 miles southeast of the Delaware River. Like the other formations of the Coastal Plain wedge the unit dips southeast, and its top is about 2,140 feet below sea level at Atlantic City, N. J. Near the outcrop the combined thickness of the Wenonah and Mount Laurel sands ranges from 35 to 100 feet and is greatest in southwestern New Jersey. Downdip toward the coast, the thickness may exceed 110 feet.

For the most part, the beds of sand in the unit are moderately permeable. Thompson (1930) reported laboratory coefficients of permeability of about 570 and 890 gpd per square foot for sand samples from the upper and lower parts of the aquifer, respectively. An average coefficient of permeability for the aquifer in New Jersey might be in the range of 500-700 gpd per square foot (Barksdale, Greenman, Lang, and others, 1958); hence the coefficient of transmissibility of an average section 70 feet thick would be about 35,000-50,000 gpd per foot. However, one pumping test at Bradley Beach, Monmouth County, N. J., gave a transmissibility coefficient of only about 7,000 gpd per foot (Lang, S. M., written communication). The storage coefficient for this test was 0.0001, which is indicative of confined conditions.

Few data are available on the productivity of wells in the Wenonah and Mount Laurel sands. From the known properties of the aquifer it may be inferred that properly constructed wells of large diameter penetrating the entire aquifer should yield about 40 or 50 to 200 gpm.

Navesink Marl

Within the basin the Navesink marl and the overlying formations, the Red Bank sand and especially the Hornerstown marl, form an imperfect or leaky aquiclude overlying the aquifer formed by the Wenonah and Mount Laurel sands. The Red Bank sand supplies only small amounts of water to wells within the basin and is missing in much of central and southern New Jersey; so in that area the Navesink and Hornerstown marls form one aquiclude having generally similar characteristics. In Delaware the Navesink marl is similar to the underlying Mount Laurel sand and together with that formation forms a poor aquifer south of the Chesapeake and Delaware Canal and an imperfect aquiclude north of the canal.

The Navesink marl consists of a green glauconitic limy clay and sand and a basal bed of shells. Clay is most abundant in the upper part of the formation. Its maximum thickness within the basin is about 40 feet, diminishing toward the south to 25 feet or less. The combined thickness of the Navesink and Hornerstown marl ranges from 35 to 70 feet.

Red Bank Sand

The Red Bank sand is fairly coarse grained, and contains clay and some glauconite in the lower part. In outcrop the sand is typically yellow or reddish-brown owing to oxidation of the iron-bearing minerals, but in subsurface the color is commonly dark grey. White micaceous sand and dark clay occur locally as do some beds cemented by iron oxide. In Monmouth County, N. J., an upper member--the Tinton sand member--consists of somewhat cemented glauconitic, clayey sand.

The Red Bank sand attains a thickness of 185 feet in the northeastern part of the Coastal Plain, outside the basin, but thins southward and is missing altogether in central and southern New Jersey. It occurs again in Delaware where it is less than 20 feet thick.

Few hydrologic data are available on the Red Bank sand, but it is believed to be similar in physical properties to the Englishtown sand (Barksdale, Greenman, Lang, and others, 1958). Within the basin it is not thick enough to be developed for more than domestic supplies, but outside the basin it yields considerable quantities of water to wells in Monmouth and northwestern Ocean Counties, N. J.

Hornerstown Marl

The Hornerstown marl, lowest formation of Tertiary age in the Coastal Plain (table 1), is scarcely distinguishable from the Navesink marl, which underlies it in much of the area. In the northeastern part of the Coastal Plain in New Jersey and in Delaware the 2 formations are separated by the Red Bank sand, but in central and southern New Jersey the Hornerstown and Navesink marls together form an aquiclude 35-70 feet thick. The maximum thickness of the Hornerstown is about 55 feet, in Monmouth County, N. J., where it confines the water in the Red Bank sand--an aquifer of some importance in that area.

The Hornerstown marl is not a true marl--an unconsolidated sediment containing a considerable amount of carbonate as the term is defined geologically--but actually is a dark-green to greenish-black glauconite or greensand mixed with some glauconitic clay and nonglauconitic sand. Toward the southwest, sand and clay become more abundant, and in Delaware it is difficult to distinguish the Hornerstown marl from the overlying Vincentown sand. At some places the sandy phases of the Hornerstown yield small supplies of water for domestic use.

Vincentown Sand

The Vincentown sand gradationally overlies the Hornerstown marl and underlies nearly all the Coastal Plain southeast of the outcrop of the Hornerstown marl. However, the outcrop of the Vincentown, itself, is missing in eastern Salem County, Gloucester County, and Camden County, N. J., where it is overlapped by the Kirkwood formation (pl. 6).

The Vincentown sand consists of a fossiliferous and somewhat consolidated limy sand, and a sparsely glauconitic quartz sand. The limy sand is more abundant within the basin, whereas the quartz sand is more abundant in the upper part of the formation, especially northeast of the basin in Monmouth County, N. J.

Down the dip the sand beds pinch out and are replaced by beds richer in clay and glauconite. This change, which occurs within about 5-7 miles of the outcrop, greatly restricts the area in which the Vincentown is useful as an aquifer. The formation also thickens downdip toward the southeast from 25-100 feet in outcrop to about 460 feet at Atlantic City, N. J., (pl. 5).

No data are available on the coefficients of permeability, transmissibility, and storage of the Vincentown sand. However, the quartz sand is at least moderately permeable, as may be inferred from its medium to coarse grain size and from well-yield information. The limy sand probably is less permeable because of its cementation and somewhat smaller average size of grains.

Yields of wells in the Vincentown sand range rather widely owing in part to the variability in thickness and permeability of the formation from place to place. Well yields as much as 300 gpm are reported from the thicker parts of the aquifer in Monmouth County, N. J., and in the vicinity of Salem, N. J., but elsewhere, yields of 50-100 gpm are more common (Barksdale, Greenman, Lang, and others, 1958). Properly constructed wells might be expected to yield 40 or 50 to 400 gpm at most places in the aquifer (pl. 9).

Manasquan and Shark River Marls

The Manasquan marl crops out in a discontinuous belt generally less than a mile wide from Clementon in eastern Camden County, N. J., to the vicinity of Long Branch in Monmouth County, N. J. (pl. 6). Overlap by the Kirkwood formation creates the long gaps in this belt, and parts of the beveled edge of the Manasquan marl are covered by Quaternary deposits. Beneath the surface the Manasquan is present in most of that part of New Jersey east of a line from Cape May to the outcrop at Clementon. The Shark River marl overlies the Manasquan and is known only in Monmouth County, N. J. In outcrop the maximum thickness of the Shark River marl is about 11 feet, and of the Manasquan marl, about 25 feet. In subsurface the combined unit thickens southeastward to about 200 feet at Atlantic City, N. J.

The lower part of the Manasquan marl is composed chiefly of glauconite (greensand), whereas the upper part is composed of an ashy mixture of very fine-grained sand and greenish-white clay. The Shark River marl consists of a mixture of greensand and light silty clay in which the uppermost 2-3 feet is cemented.

The Manasquan and Shark River marls form an aquiclude confining water in the Vincentown sand. Where the Vincentown is productive, the aquiclude is not more than 25 feet thick and contains beds having moderate permeability; therefore it probably is not very effective as an aquiclude.

Piney Point Formation

The Piney Point formation does not crop out within the basin and was not recognized as a distinct aquifer in the area until Marine and Rasmussen (1955) described the formation in Delaware.

The Piney Point occurs only beneath the southern part of the Coastal Plain--beneath Kent and Sussex Counties, Del., and in the southern parts of Cumberland, Cape May, and Atlantic Counties, N. J. It rests on a surface eroded across the Manasquan marl, Vincentown sand, and Hornerstown marl; in turn it is overlain unconformably by the Kirkwood formation. In thickness the Piney Point formation ranges from nearly nothing along its northern edge where it wedges out between the overlying and underlying formations to about 290 feet at Atlantic City, N. J.

As determined entirely from well samples, the Piney Point formation consists of beds of coarse- to fine-grained glauconitic, salt-and-pepper-colored sand and greenish-gray clay.

All water in the formation is confined and is subject to recharge only from adjacent beds, especially where they are relatively permeable. No data on its water-yielding character are available, because the formation has been developed only slightly for water supplies.

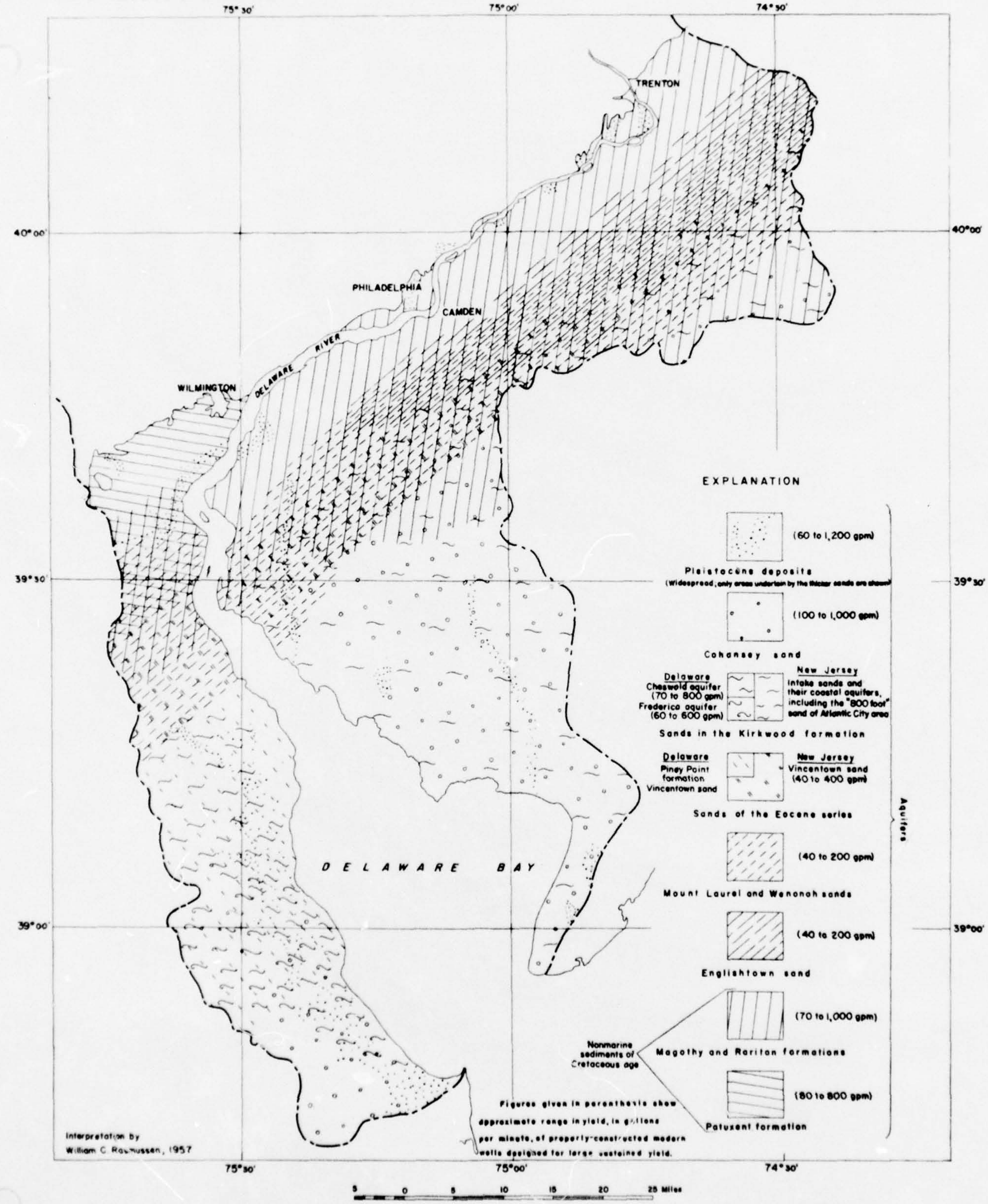
Kirkwood Formation, an Important Group of Aquifers and Aquicludes

The Kirkwood formation, which contains several important aquifers in the Coastal Plain of New Jersey and Delaware, underlies practically all the Cohansey sand in New Jersey and crops out in a northeast-trending belt inland from the outcrop of the Cohansey (pl. 6). The Kirkwood does not crop out in Delaware, but it underlies the Quaternary deposits in approximately the southern two-thirds of the State (compare pls. 6 and 7). It extends seaward beneath the Cohansey sand and, where sea-water encroachment has not resulted from pumping of wells, contains fresh water beyond the present shoreline. The Kirkwood also underlies most of Delaware Bay.

The Kirkwood formation lies on a buried surface of very low relief cut on formations ranging down in the sequence from the Piney Point formation to the Navesink marl (table 1). Throughout most of its extent, however, it overlies the Manasquan marl or the Vincentown sand. The lower part of the formation dips about 25 feet per mile to the southeast, whereas the upper part dips a little more than 10 feet per mile. The thickness ranges from nearly zero along its northwest edge to probably more than 700 feet beneath the mouth of Delaware Bay.

U S GEOLOGICAL SURVEY

PLATE 9



MAP OF COASTAL PLAIN IN DELAWARE RIVER BASIN
SHOWING PRODUCTIVITY OF AQUIFERS

Preliminary and subject to revision

In outcrop the Kirkwood formation consists chiefly of fine-grained micaceous, quartzose sand alternating with layers of silt and clay of variable thickness. Locally, beds of lignitic black clay are prominent. The Shiloh marl member, a highly fossiliferous clayey or silty sand, occurs at the top of the formation in southern New Jersey.

In subsurface the proportion of silt and clay increases down the dip toward the coast, but the beds of sand become coarser grained and more permeable. Silt and clay are estimated to constitute at least four-fifths of the total thickness of the Kirkwood formation at Atlantic City (Barksdale, Greenman, Lang, and others, 1958).

Several prominent sandy zones in the Kirkwood have been designated as aquifers: The Cheswold aquifer in Delaware, and its possible equivalent, the "800-foot" sand, at Atlantic City, N. J.; the Frederica aquifer in Delaware, separated from the underlying Cheswold aquifer by about 100 feet of silt and clay; and some aquifers above the "800-foot" sand in coastal New Jersey, the highest of which may be equivalent to the Shiloh marl member or to the Frederica aquifer.

Because of the absence of deep wells through much of the extent of the Kirkwood formation, particularly in southern New Jersey between the coast and the area of outcrop, probably not all the aquifers in the Kirkwood formation are known.

Field and laboratory tests to date have indicated only moderate permeabilities for the aquifers in the Kirkwood formation. Laboratory-determined coefficients of permeability for several samples of the "800-foot" sand at Atlantic City averaged about 860 mgd per foot (Thompson, 1928). A pumping test made in 1952 in the same area gave a closely comparable average coefficient of about 880 gpd per square foot for an 80-foot thickness of aquifer. Elsewhere, pumping tests and estimates based on yields of individual wells have yielded smaller values--in the order of 100-500 gpd per square foot.

Coefficients of transmissibility derived in pumping tests range from 9,000 to 70,000 gpd per foot, and coefficients of storage determined so far are all about 0.0003, except in one test at Ancora, N. J. which gave a value of 0.0004. The remarkably consistent values of storage coefficient may be just an accident because of the small statistical sample. These coefficients are representative of confined conditions.

Cohansey Sand, an Aquifer of Great Potential

The Cohansey sand, perhaps the most promising future source of ground-water supplies in the Coastal Plain of New Jersey and Delaware occurs at or near the land surface throughout most of the outer part of the Coastal Plain in New Jersey--an area of about 2,500 square miles, of which about 1,000 square miles is within the basin (pl. 6). The Cohansey may be present also in southern Delaware, but owing to the difficulty of distinguishing it from the overlying Quaternary deposits, its presence there has not been confirmed. In New Jersey much of the Cohansey sand is blanketed by the Quaternary deposits--chiefly the Bridgeton and Cape May formations--which are generally thin but attain a thickness of about 200 feet in buried valleys and in places along the coast. The outcrop of the Cohansey is a gently seaward-sloping plain of low relief characterized by extensive marshes along most of the streams.

The Cohansey sand lies on a buried surface of low relief eroded on the Kirkwood and older formations. The dip of beds in the Cohansey averages about 10 feet per mile to the southeast, and the formation extends seaward beyond the coast, beneath the Quaternary deposits (pl. 5). The thickness of the formation ranges from nearly zero where beveled by erosion along its northwestern margin to about 265 feet at Atlantic City on the coast.

The Cohansey consists largely of typically light-colored quartzose, somewhat micaceous sand, but it also contains lenses of silt and clay as much as 25 feet thick, and some gravel. The sediments probably were deposited in estuaries and deltas except toward the southeast where they may have been deposited in the ocean. The average grain size of the materials decreases southeastward; and beds of silt and clay become thicker and more abundant near the coast.

On the whole, the Cohansey sand is a highly permeable formation. The coefficient of permeability of the well-sorted medium- to coarse-grained sand probably is exceeded only by some of the sand and gravel in the glacial-outwash and channel-fill deposits of Pleistocene age. Coefficients of permeability for the Cohansey, determined from pumping tests made in Cumberland, Atlantic, and Cape May Counties, N. J., range from about 500 to more than 5,000 gpd per square foot and averaged more than 1,000 gpd per square foot (table 3).

The transmissibility ranges from moderate to high, depending in part on the thickness of the aquifer. Coefficients of transmissibility determined from the pumping tests cited in table 3 range from about 40,000 to more than 200,000 gpd per foot. All these values are based on less than complete penetration of the Cohansey and hence are too

Table 3.--Coefficients of transmissibility, permeability, and storage in Cohansey sand

Location	Coefficient of transmissibility (gpd per ft)		Thickness of aquifer (ft)	Coefficient of permeability (gpd per sq ft)		Coefficient of storage (dimensionless)		Source of data
	Range	Midpoint between extremes		Range	Midpoint between extremes	Range	Midpoint between extremes	
Rio Grande, N.J. Nov. 1957	55,000- 87,000	71,000	45±	1,200-1,900	1,600	0.0006-0.003	0.0016	USGS unpubl. data
Rio Grande, N.J. Oct. 1952	41,000- 56,000	48,000	45±	910-1,200	1,100	.0008- .002	-	do
Linwood, N. J.	92,000-100,000	98,000	120	770- 880	-	.0005- .0005	.0005	do
Seabrook, N. J.	57,000-220,000	150,000 1/ 180,000 2/	40±	1,400-5,500	4,200 3/	.0002- .0004	.0003	do
Pleasantville, N. J.	-	73,000	70±	500-1,400	1,000	-	-	do

1/ Average of tests in west part of area
2/ Average of tests in east part of area
3/ Average of tests in all the area

low to be representative of the full thickness. Even so, they are comparable to transmissibility coefficients determined for the aquifers that at present are most productive--those in the nonmarine sediments of Cretaceous age (table 2).

The coefficients of storage from the tests listed in table 3 range from 0.0008 to 0.002 --values representative of confined to semiconfined conditions rather than of unconfined conditions. Such storage coefficients are not representative of the specific yield, which as determined by laboratory tests, is about 0.25. If pumping of the confined sands should proceed at any place to the point where the piezometric surface falls below the confining layers, then values of the coefficient of storage would approach or equal the specific yield.

Modern drilled wells in the Cohansey sand may reasonably be expected to yield between 100 and 1,000 gpm and even higher yields may be obtained without excessive drawdown in places where the thickness of the aquifer exceeds 100 feet.

Beacon Hill Gravel - a Remnant Cap

The Beacon Hill gravel, or Bryn Mawr gravel as its probable equivalent is called in the Piedmont province (Richards, 1956), occurs at widely scattered places where it caps broad hills and ridges. The Beacon Hill occurs at only 2 places in the portion of the Coastal Plain within the basin but caps about 25 hills outside the basin in Monmouth, Ocean, and Burlington Counties, N. J. (pl. 6). In the Piedmont in southeastern Pennsylvania and northern Delaware the Bryn Mawr gravel caps several broad interstream areas at altitudes of about 300 feet.

The Beacon Hill gravel consists of highly weathered deposits of sand, gravel, silt, and some clay which are in places cemented by iron oxide. Some of the pebbles are so weathered that they crumble to tripoli--a friable or dustlike silica. The Pliocene(?) age listed in table 1 is uncertain, because no fossils have been found in the formation.

Because of its position on hilltops above the water table, wells in the outcrop pass through the Beacon Hill gravel into saturated materials below. Therefore its hydrologic significance lies in its function as a moderately to highly permeable intake area for the underlying formations (pl. 8).

Quaternary Deposits--an Important Group of Aquifers and a Portal for Ground-Water Recharge and Discharge

In the Coastal Plain the unconsolidated sediments of Quaternary age comprise several geologic formations and units that overlie the older formations as valley fills, thin blanketlike masses, and scattered caps on ridges and hills. With the exception of relatively thin deposits of Recent age along streams, marshes, and beaches, these deposits were laid down during the Pleistocene epoch, or Ice Age, as it is often called. All the deposits therefore are less than about a million years old and are much younger than the underlying Cretaceous and Tertiary formations (table 1). The Quaternary deposits are shown on a separate geologic map (pl. 7) because they mask the Cretaceous and Tertiary formations so extensively in some areas that the relations of those formations could not be shown on the same map with the Quaternary formations. The extent of some of the Quaternary formations has not been defined accurately in much of the region, partly because of the lack of detailed geologic study but at many places also because of the difficulty of distinguishing these formations from the underlying formations of Cretaceous and Tertiary age.

Bridgeton and Pensauken Formations

The Bridgeton formation and younger Pensauken formation are blanketlike deposits of quartzose gravel, sand, and silt in broad interstream areas in the Coastal Plain (pl.7). The Bridgeton is generally somewhat more highly weathered than the Pensauken but the two formations are very similar. In places it is difficult to distinguish the Bridgeton from the coarser phases of the underlying Cohansey sand.

The Bridgeton lies at altitudes more than 150 feet above sea level in central New Jersey and above 100 feet in southern New Jersey, whereas the altitude of the base of the Pensauken declines southward from about 100 feet in the area between South Amboy and Camden, N. J., to 30 feet south of Salem, N. J. The Pensauken occurs also northwest of the Fall Line in Pennsylvania where it lies at altitudes of as much as 170 feet above sea level (Bascom, Clark, Darton, and others, 1909, p. 12).

Both the formations were deposited in broad valleys by the ancestral Delaware River and its tributaries. The Bridgeton formation is as much as 70 feet thick, but the Pensauken generally does not exceed about 20 feet in thickness (Campbell and Bascom, 1933).

Although these formations are extensive in many parts of the Coastal Plain (pl. 7), they are scarcely thick enough to provide large supplies of water to wells. Nonetheless, they act as permeable entry areas for ground-water recharge, and where they overlie permeable formations such as the Cohansey sand and permeable beds in the non-marine Cretaceous sediments, they constitute water-table aquifers in conjunction with those formations, as shown in the schematic diagram, (pl. 8). Where they overlie aquicludes or less permeable beds the Bridgeton and Pensauken probably are capable of yielding only small supplies sufficient for domestic or small-farm uses. In such situations the water they contain discharges naturally along a line of seeps or small springs near their base.

Unclassified Deposits of Pleistocene Age

The unclassified deposits of Pleistocene age include a variety of materials that do not belong to the Bridgeton, Pensauken, Cape May or Talbot formation and whose proper assignment awaits the findings of future field investigations. In Delaware these deposits were assigned to the Wicomico formation in the U. S. Geological Survey Geologic Atlas Folios (Miller, 1906; Bascom and Miller, 1920). In New Jersey the unclassified deposits were described in the U. S. Geological Survey Folios as a discontinuous mantle of surface material whose age, in many places, is not determinable. Owing to their thinness and uncertain extent the unclassified deposits in New Jersey are not shown on plate 7.

The Wicomico formation in Delaware is described as a broad blanketlike deposit of loam, sand, gravel, and scattered boulders which lies topographically above the adjacent younger Talbot formation (Miller, 1906). The Wicomico, which is as much as 50 feet thick, is reported to be somewhat fine grained toward the top.

In New Jersey the unclassified deposits include a variety of materials ranging from silt and clay to coarse-grained sand and gravel. The deposits generally are only a few feet thick and at many places they closely resemble the weathered parts of the underlying formations of Cretaceous and Tertiary age.

The hydrologic properties of the unclassified deposits are not well known. Probably they serve primarily as a moderately to highly permeable blanket through which recharge enters the underlying aquifers or through which ground water discharges. In Delaware, buried valleys or channels filled by deposits provide large yields to favorably situated wells.

Cape May and Talbot Formations

The Cape May formation and its probable equivalent in Delaware, the Talbot formation, form a roughly wedge-shaped mass thinning inland and having tonguelike extensions up the larger stream valleys. The Cape May includes broad, blanketlike deposits and channel-fill or valley-fill deposits which may be more than 100 feet thick in northern Delaware. The exact relations of the Cape May formation to the glacial outwash to the north are not known, but the coarse-grained gravelly deposits in the broad valley adjacent to the Delaware River near Trenton, N. J., have been described both as outwash and as Cape May formation in earlier reports (compare Greenman, 1955, and Bascom, Darton, Kümmel, and others, 1909). Richards (1956, p. 89) believes that no sharp lines exists between the Cape May formation and the glacial outwash. Parts of the Cape May formation near the coast are of marine origin, and the upper part of the formation includes estuarine deposits of clay and silt.

Much of the Cape May and Talbot formations consists of stream-deposited sand and gravel that are much less weathered than the deposits of the Bridgeton and Pensauken formation. Where such deposits lie in buried valleys more than 100 feet deep, large yields may be obtained from drilled wells. Rasmussen and others (1957, p. 124) reported yields of as much as 1,000 gpm from drilled wells in these buried valleys in Delaware. At present, however, the location of the buried channels and valleys is known only in a general way in northern Delaware and in Cape May County, N. J.

Toward the coast the estuarine deposits of clay and silt in the upper part of the Cape May formation confine the water in the underlying deposits of sand and gravel. The top of this silt-clay aquiclude is as much as 30 feet above sea level, but the underlying sand and gravel extend below sea level; therefore the ground water of these deposits is hydraulically continuous with sea water. Such conditions make it possible for salt-water encroachment to take place where pumping has lowered water levels below sea level. In some places encroachment already has occurred.

Together with the glacial outwash the Cape May and Talbot formations constitute one of the most promising sources of ground-water supplies in the southern part of the Delaware River basin. Yields of several thousand gallons per minute to individual wells are possible in places, especially where recharge may be induced from adjacent streams and other fresh-water bodies.

Basin-Rim Sand

Throughout parts of the Coastal Plain are small, generally elliptical basins, the rims of which, and in places the interiors, are formed by deposits called basin-rim sand (Rasmussen, 1953). The upper part consists of fine-grained sand and silt, whereas the lower part is a deposit of reddish-brown poorly sorted coarse-grained sand and gravel.

The basins collect runoff, allowing it to infiltrate to the ground-water body, or where the underlying materials are saturated, the basin centers are sites for large evapotranspiration losses. Thus the basins function as portals for recharge or discharge of ground water, or for both at different times of the year.

Glacial Outwash and Alluvium

The glacial outwash was deposited by streams flowing from the continental glaciers that occupied the northern part of the basin. The most extensive and permeable outwash deposits in the Coastal Plain are those of the Wisconsin glacial stage that occupy the broad valley adjacent to the Delaware River near Trenton. Older outwash deposits are herein grouped with the Pensauken formation and possibly the Bridgeton formation. Thin alluvium of Recent age is grouped with the underlying outwash of Wisconsin age because of the difficulty in differentiating the 2 deposits and because they are hydraulically connected. The glacial outwash appears to be mixed with similar deposits of the Cape May formation downstream from Trenton, N. J., (pl. 7).

The glacial-outwash deposits which are largely relatively unweathered sand and gravel, are highly permeable and yield as much as 1,050 gpm to wells in southeastern Bucks County, Pa., (Greenman, 1955, p. 39). The outwash is quite similar in hydrologic properties to the coarse-grained part of the Cape May formation.

Marsh and Swamp Deposits

The marsh and swamp deposits occur along the streams and tidal estuaries and consist of dark silt and clay mixed with organic matter. They are all or partly covered by water most of the time and generally are in such a loose, flocculent state that appreciable recharge and discharge may pass through them. Along bays and estuaries the marsh deposits may serve as portals for salt-water encroachment into underlying shallow aquifers in which the hydraulic head has been lowered below sea level by pumping or by drainage operations that reduce freshwater head above sea level. Under natural conditions the fresh-water marshes and swamps are probably the sites of great quantities of ground-water discharge.

Beach and Dune Sands

The beach and dune sands consist of loose well-sorted sands along the beaches and offshore bars. The total thickness of these deposits probably does not exceed 30 feet, except near Lewes, Del., where dunes are as much as 80 feet high. The beach and dune sands act as a permeable collector for recharge which in places may be transmitted to the underlying Cape May formation. Also, they locally provide small supplies of fresh water for domestic use along the shore.

RECHARGE AND DISCHARGE

Under natural conditions the aquifers of the Coastal Plain are recharged largely by infiltration of precipitation on their intake areas, which consist either of the outcrops themselves, or the overlying blanket of Quaternary deposits (pl. 8). Seepage from the headwater reaches of streams may contribute a small amount of additional recharge.

Some buried aquifers receive recharge from adjacent aquifers across the intervening aquicludes, but such recharge does not constitute a net gain of water in the system.

The average rate of natural recharge to the Coastal Plain aquifers has not been determined directly. However, a 2-year water budget was made by Rasmussen and Andreasen (1958) for the drainage basin of Beaverdam Creek, an area of 19.5 square miles in the Coastal Plain of Maryland about 50 miles southwest of the mouth of Delaware Bay. The physical and climatic conditions at Beaverdam Creek are believed to be similar to those in the aquifer intake areas in most of the Coastal Plain in New Jersey and Delaware. Rasmussen and Andreasen found that the average rate of infiltration or recharge was a little more than 1 mgd per square mile, which amounted to slightly more than half the average annual rate of precipitation.

A semi-independent check of the results of the Beaverdam Creek study is provided by an analysis of precipitation and runoff data in the Coastal Plain of New Jersey and Delaware. Table 4 summarizes the data derived from maps prepared by the U. S. Geological Survey and the U. S. Weather Bureau showing precipitation, water loss, and runoff, and from base-flow recession curves and streamflow hydrographs developed by the Geological Survey.

The values of precipitation, water loss, and runoff are averages for a 30-year period (1921-50) and thus are virtually unaffected by any change in the quantity of water in storage during the period. The last item--base-flow, chiefly ground-water runoff--indicates the lower limit of the ground-water discharge, and also the lower limit of groundwater recharge, because not all ground-water recharge eventually is

discharged into streams; a large part is discharged as evapotranspiration, and some ground water in the Coastal Plain is discharged directly to the estuaries, bays, and ocean as unmeasured outflow. Total ground-water discharge, then, includes a part of the water loss in table 4 as well as all the base flow (ground-water runoff).

Total ground-water recharge--or discharge--may be calculated as the sum of the base flow of streams, the discharge of ground water by evapotranspiration, and the unmeasured ground-water outflow beneath and between streams. Two methods of calculating the recharge or discharge are used in the following example. In both methods the base flow is estimated to average about 0.6 mgd per square mile (table 4); and on the basis of the Beaverdam Creek study (Rasmussen and Andreasen, 1958), ground-water discharge by evapotranspiration is estimated to be about 40 percent of the total evapotranspiration loss.

In the first method, unmeasured ground-water outflow is assumed to be negligible; hence all the water loss in table 4 is assumed to represent evapotranspiration. Thus, base flow (0.6 mgd per sq mi) + ground-water discharge by evapotranspiration (0.4 x 1.2 = 0.5 mgd per sq mi) = total ground-water recharge or discharge (1.1 mgd per sq mi).

Table 4.--Water budget for Coastal Plain of Delaware River basin and New Jersey

Item	Approximate range (mgd per sq mi)	Average (mgd per sq mi)	Average percent of precipitation	Average percent of runoff
Precipitation	1.9 - 2.3	2.1	100	-
Water loss 1/	1.1 - 1.4	1.2	57	-
Runoff	.65- 1.2	.9	43	100
Direct runoff	-	.3	14	33
Base flow (chiefly ground-water runoff)	-	.6	29	67 2/

1/ Largely evapotranspiration, but includes some unmeasured ground-water outflow.

2/ Estimated value based on an interpretation of base-flow recession curves and streamflow hydrographs for Coastal Plain streams in the Delaware River basin and New Jersey. The value for Beaverdam Creek basin, Md., was nearly 72 percent (Rasmussen and Andreasen, 1958), or, allowing for change in storage during the budget period, perhaps 74 percent.

In the second method, unmeasured ground-water outflow is assumed to be 0.2 mgd per square mile (probably a maximum, rather than a likely value); hence, the total evapotranspiration loss is reduced from 1.2 mgd per square mile (table 4) to 1.0 mgd per square mile. Thus, base flow (0.6 mgd per sq mi) + ground-water discharge by evapotranspiration (0.5 x 1.0 = 0.4 mgd per sq mi) + unmeasured ground-water outflow (0.2 mgd per sq mi) = total ground-water recharge or discharge (1.2 mgd per sq mi).

These values are approximate averages for the entire Coastal Plain in the Delaware River basin and New Jersey and are in approximate agreement with unpublished U. S. Geological Survey data obtained from hydrologic studies at Brookhaven, Long Island, N. Y. Rather large deviations from the averages might be expected in parts of the area, as indicated by the ranges in values of precipitation, water loss, and runoff shown in table 4. The average values also apply approximately to the part of the Coastal Plain entirely within the Delaware River basin.

The estimated recharge is in close agreement with, though a little greater than, the 1 mgd per square mile estimated for the Beaverdam Creek basin. The slightly higher recharge estimated for the Coastal Plain of New Jersey and Delaware may reflect its somewhat greater average precipitation--2.1 mgd per square mile--as compared with 1.97 mgd per square mile for the budget period at Beaverdam Creek. In any case, an estimated average recharge of 1.1 mgd per square mile for the Delaware River basin and adjacent Coastal Plain is assumed, and is believed to be conservative.

The area of the Coastal Plain in the Delaware River basin, excluding salt-water marshes, bays, and estuaries, is about 2,750 square miles. Thus, if the average recharge for this area is 1.1 mgd per sq mi, the average recharge to ground water in the Coastal Plain in the Delaware River basin is about 3,000 mgd. By comparison, this is equivalent to about 40 percent of the flow of the Delaware River at Trenton, N. J., which is about 7,600 mgd, and which represents the runoff from that part of the basin above Trenton, about 6,780 square miles. As another comparison, discharge from pumped wells in the Coastal Plain of the basin was estimated to average about 210 mgd for 1956-57, which is 7 percent of the estimated total natural ground-water discharge of 3,000 mgd. But part of the water pumped returns to the aquifers; hence, the net discharge of ground water by pumping is even less than 7 percent of the natural discharge. Aquifers in the nonmarine sediments of Cretaceous age--the lowest in this wedge of deposits in the Coastal Plain -- yield the largest proportion of the total ground-water pumpage at present (slightly more than half in 1956-57), but the deposits of Quaternary age are becoming increasingly important, and the Cohansey sand offers perhaps the greatest potential for future development.

As a rough approximation, given only to indicate order of magnitude, the potentially available ground-water supply in the Coastal Plain part of the Delaware River basin is assumed to equal the average discharge of ground water as base flow in streams--0.6 mgd per square mile (table 4). This assumption is conservative, because part of the natural discharge of ground water by evapotranspiration also may be recovered for use as water levels are lowered by increased pumping. Hence, the potentially available ground-water supply within the Coastal Plain of the basin is estimated to be 0.6 mgd per square mile x 2,750 square miles = about 1,600 mgd. Therefore, present use (1956-57) is about one-eighth of this potential, but because part of the water pumped is not consumed and returns to the aquifers, the net discharge of ground water by pumping is less than one-eighth of the potential. However, because of practical limitations, chiefly economic, it is estimated that only about one-half of the potential ground-water supply, or about 800 mgd, can be developed. It should be emphasized, moreover, that the ground-water supply is merely a part of the total water supply, including water from surface sources. Should it prove more feasible to develop most of the supplies from surface sources rather than from ground water, the ground-water supply that could feasibly be developed in the Coastal Plain might be substantially less than 800 mgd.

Pumping of ground water has induced recharge from streams and other bodies of surface water where pumping has reversed the natural hydraulic gradients toward the surface-water bodies. Where the surface-water bodies are fresh, the induced recharge augments the ground-water supply; but where the surface-water bodies are salty, the saline water replaces the pumped fresh water in the aquifers.

The largest amount of induced recharge occurs along the Delaware River estuary below Trenton, N. J., where several well fields on both sides of the estuary are withdrawing large amounts of water from the nonmarine sediments of Cretaceous age. The present amount of induced recharge is not known, but the potential amount under a planned system of development may exceed 100 mgd (Barksdale, Greenman, Lang, and others, 1958).

Over a long enough period of time changes in storage can be ignored because recharge approximately equals discharge. By far the greater proportion of total discharge occurs at natural outlets--stream channels, estuaries, bays, the ocean, springs and seeps, lakes and ponds--and in marshes, and other low-lying lands where the water table is sufficiently near the land surface to allow discharge by evapotranspiration. Determination of the magnitude of the discharge through these outlets would require detailed water-budget studies which are costly in terms of time, efforts, and money. As a consequence such studies have only been attemped in a few places in this part of the country. However, the approximate magnitude of discharge to streams and as evapotranspiration was indicated in the preceding discussion (p. 38, 39), and is believed to be sufficiently accurate that, except in unusual circumstances of local importance, such costly water-budget studies need not be made.

PATTERNS OF MOVEMENT

Where not affected by pumping, most ground water in the Coastal Plain moves from high parts to low parts of the intake areas or to the outcrops of the aquifers (pls. 6 and 7); the quantity moving through the aquifers and aquicludes downdip from the intake areas is relatively small (Barksdale, Greenman, Lang, and others, 1958), even though the quantity in storage is very large. In the intake areas the water either is unconfined or is semiconfined by inextensive layers of silt and clay, and the configuration of the water table is somewhat like that of the land surface except that it is more subdued and regular. Hydraulic gradients are relatively steep and they slope toward areas of discharge: (1) Near the base of the aquifers; or (2) along stream channels and marshes. The gradients are much gentler in the confined or artesian parts of the aquifers, which accounts for the smaller quantities of water movement in the artesian systems.

Unfortunately, comprehensive, regional water-level data are lacking for nearly all the aquifers in the Coastal Plain of New Jersey and Delaware. Almost all water-level data are for small areas in and near well fields, where the native pattern of ground-water movement has been altered radically by pumping, and it would be impossible now to reconstruct the original water tables and piezometric surfaces.

Some useful information is available, however, on the native pattern of movement of water in the nonmarine sediments of Cretaceous age. Plate 10 shows the theoretical flow pattern in the nonmarine sediments under natural conditions, as postulated by Barksdale, Greenman, Lang, and others (1958, fig. 18). The theoretical flow pattern is based on several simplified assumptions and does not, therefore, indicate the actual conditions in detail.

For example, the interface between salt water and fresh water is not a sharp vertical line as shown in plate 10; rather, it probably is a zone of some thickness and is more nearly horizontal than vertical. Thus, the inland extent of salt water is considerably greater in the lower part of the unit than in the upper part.

However, the map is believed to show adequately the general pattern of ground-water movement and the extent of fresh water in the nonmarine sediments before their development. In part, the validity of the theoretical flow pattern is confirmed by the earliest water-level data for wells penetrating the nonmarine sediments, and the position of the interface between salt water and fresh water is substantiated in a general way at a few places where deep wells either have been drilled on both sides of the interface or have penetrated it (Barksdale, Greenman, Lang, and others, 1958).

The map shows that most of the water that moves through the buried, artesian portion of the nonmarine sediments travels circuitous paths from two relatively high intake areas--one northeast of Trenton, N. J., the other in northern Delaware--to discharge areas along the Delaware River estuary below Trenton and along Raritan Bay.

Bear in mind, however, that a greater quantity of water moves in much shorter and more direct paths from high to low parts of the intake area and discharges into the Delaware and Raritan Rivers and their tributary streams.

Less is known about native patterns of movement in the other aquifers having intake areas along the inner northwest part of the Coastal Plain. In some respects, the patterns of movement probably were similar to those in the nonmarine sediments, although because high-level and low-level intake areas are not as distinct as in the nonmarine sediments and because the aquicludes are more permeable, more water moved downdip toward the ocean and bays and discharged by slow upward movement across overlying aquicludes and aquifers. As in the nonmarine sediments, the greatest quantities of water moved relatively short distances to discharge points in the outcrops or intake areas.

The predominant movement in the Cohansey sand and overlying Quaternary deposits in the outer part of the Coastal Plain was, and for the most part still is, along relatively short paths from intake points in the broad, flat interstream areas to discharge points along the adjacent streams and marshes. Longer and more devious paths are followed where there are layers of silt and clay, but such layers are not extensive or thick except near the coast or the shores of Delaware Bay.

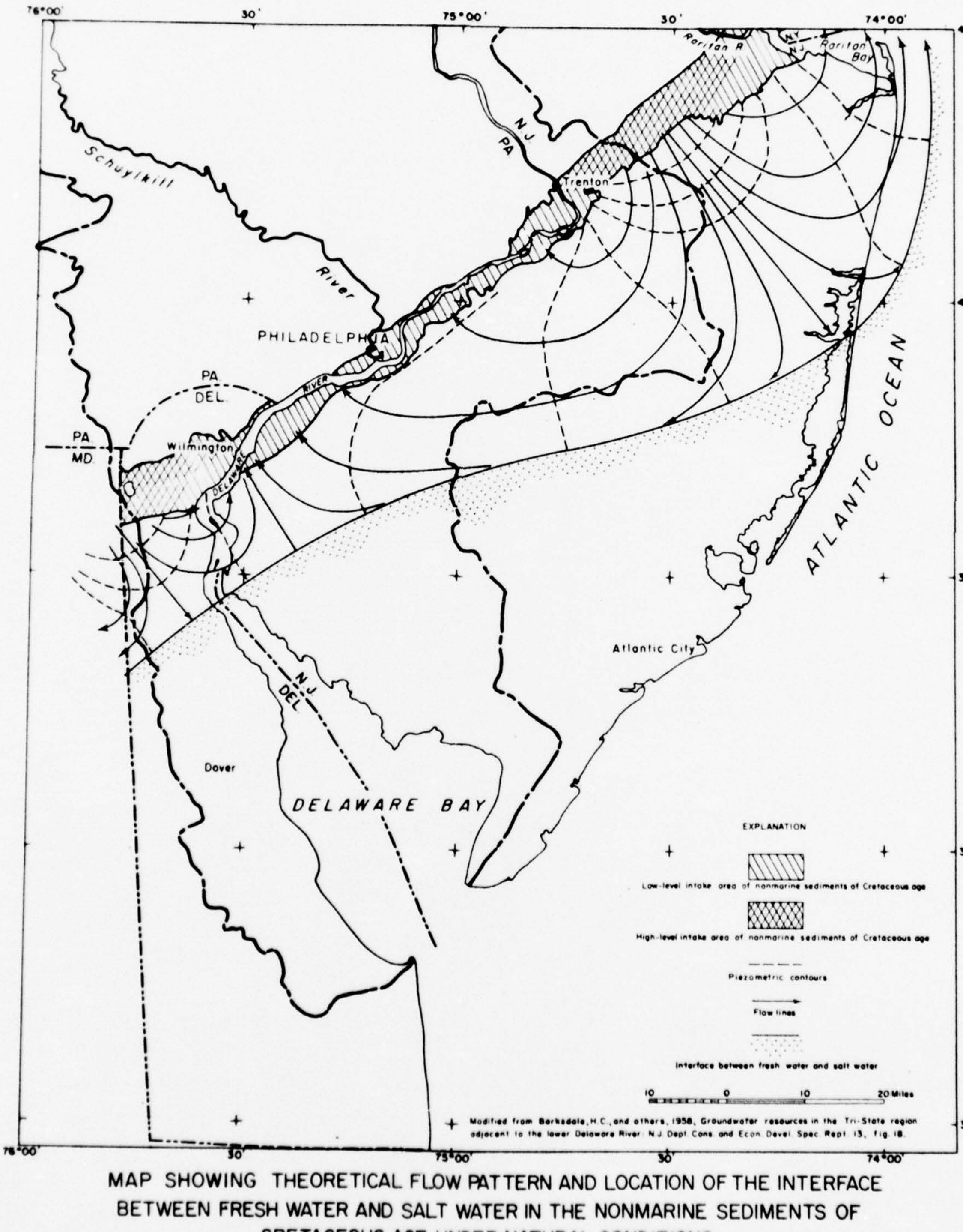
Artificial discharge through pumped wells has changed the pattern of ground-water movement considerably in parts of the Coastal Plain. Water now is diverted from natural outlets and moves toward the pumped areas, generally from all directions within the influence of the cone of depression that surrounds pumped wells.

The greatest changes have occurred in the most heavily pumped areas, principally along the Delaware River estuary from Trenton, N. J., to northern Delaware, in the vicinity of Raritan Bay, and along the coast of New Jersey.

Large-scale pumping of ground water from wells in the nonmarine sediments along the Delaware River estuary in places has diverted water from its former paths leading to discharge points in the channel and has induced movement from the river into the aquifers at those places. Also, hydraulic gradients from the intake areas have been increased, and the loss of natural discharge to the river in

U.S GEOLOGICAL SURVEY

PLATE 10



MAP SHOWING THEORETICAL FLOW PATTERN AND LOCATION OF THE INTERFACE BETWEEN FRESH WATER AND SALT WATER IN THE NONMARINE SEDIMENTS OF CRETACEOUS AGE UNDER NATURAL CONDITIONS

some cases has been exceeded by the gain in artificial discharge in the pumped areas. Some ground water has been withdrawn from storage, and recharge to the aquifers probably has increased.

Northeast of the basin, concentrated pumping in the intake area of nonmarine sediments along the Raritan and South Rivers has induced large quantities of recharge--some of it of very poor quality--from those streams (Barksdale, Greenman, Lang, and others, 1958).

Along parts of the coast in New Jersey, heavy pumping of water from artesian aquifers, particularly from the "800-foot sand in the Kirkwood formation at Atlantic City, has greatly lowered the artesian pressure. There, over an area of 20 or 30 miles along the shore, where prepumping water levels were about 25 feet above sea level, pumping has lowered the head to more than 75 feet below sea level. Thus, this represents a total head loss of more than 100 feet (Barksdale, 1945, p. 565), and has caused movement of large quantities of water downdip toward the centers of withdrawal. Almost certainly, some of the recharge to the Kirkwood formation within the Delaware River basin moves toward the major center of pumping near Atlantic City; the convergence of ground-water flow lines on the Atlantic City area has been likened to the paths of tourists in the summer. Although much of the water moves into the area from the seaward side, only slight signs of salt-water encroachment have yet been detected.

The flow pattern in the Kirkwood formation has been changed also in Kent and Sussex Counties, Del., where withdrawals from the Cheswold and Frederica aquifers have caused declines in artesian head of more than 80 feet in places (Rasmussen and others, 1957).

GROUND-WATER STORAGE

Use of Storage

The aquifers underlying the Coastal Plain constitute large ground-water reservoirs which, because of the scarcity of sites suitable for surface reservoirs, are potentially very important in the management of water supplies. The storage capacity of these reservoirs is enormous; however, the calculation of this quantity is of little consequence other than to indicate that it is very many times the annual recharge. To use more than a small part of this capacity, therefore, the average rate of withdrawal from the reservoirs would have to exceed the average rate of recharge for a long period--an overdraft procedure.

Ground-water overdraft, commonly known as "mining", is a practice common in the semiarid and arid parts of the country, but is not likely to become a widespread practice in the Coastal Plain. Such a continued overdraft of ground-water supplies would lead to salt-water encroachment, which results from lower ground-water levels near the coast.

The ground-water reservoirs of the Coastal Plain are much more likely to be used on a sustained-yield basis wherein the storage depleted during periods of excess discharge, both natural and artificial, is replenished completely either naturally or artificially during periods of excess recharge. The long-term yield of the reservoirs, then, is equal to the long-term average recharge and the storage used is that required to level out the fluctuations in recharge and discharge. In the Coastal Plain of New Jersey and Delaware, water supplies are relatively abundant and uniformly distributed in time; drought periods seldom are sufficiently long or severe to require large drafts on ground-water storage. Peak consumptive use of ground-water supplies is for supplemental irrigation of crops in the summer, at a time when natural recharge is at a minimum. Such seasonal demands can be readily met with the available ground-water storage in the shallow aquifers.

Rasmussen (1955) estimated that the usable reservoir capacity of the Coastal Plain aquifers in Delaware was sufficient to store more than a year's recharge, considering the recharge as 1 mgd per square mile of aquifer intake area. No such estimate has been made for New Jersey; however, because of the similar hydrologic and geologic conditions there, Rasmussen's estimate probably indicates the order of magnitude of usable reservoir capacity for all the Coastal Plain of this area. The capacity appears to be more than adequate to meet maximum fluctuations in ground-water storage that would occur on a sustained-yield method of operation.

Storage Fluctuations

The fluctuations in storage in an aquifer are reflected by fluctuations in the water table or piezometric surface; the ratio of the volume represented by the zone of fluctuation of the water table or piezometric surface is determined by the storage coefficient of the aquifer. For example, in a water-table aquifer having an average coefficient of storage of 0.1, a 10-foot decline in water table over a specified area represents a decline in storage equal to a 1-foot depth of water over the area. In an artesian aquifer having a coefficient of storage of 0.0001, a 10-foot lowering of the piezometric surface represents a decline in storage of only 0.001 foot of water. In a water-table aquifer where part of the material actually is drained as the water table declines, the coefficient of storage is

practically equal to the specific yield, but in an artesian aquifer none of the material is drained, and the water released from storage is derived principally from a slight expansion of the water itself and a slight decrease in the volume of the aquifer. However, an artesian aquifer becomes a water-table aquifer when the water level is lowered beyond its upper confining layer; the storage coefficient within the area of unwatering then becomes practically equal to the specific yield. Sustained-yield operation of artesian aquifers in the Coastal Plain probably would involve little dewatering, however; only in the shallower water-table aquifers, or the recharge-outcrops of the artesian aquifers where water-table conditions exist, would the upper part actually be dewatered seasonally.

Natural Fluctuations

The natural fluctuations in storage in most Coastal-Plain aquifers are small compared to the total storage capacity of those aquifers. For example, base-flow recession data for Coastal Plain streams indicate that in an average year the maximum range of fluctuation in ground-water storage supplying base or fair-weather flow to the streams amounts to less than a 3-inch depth of water over their drainage area. Fluctuations in storage caused by changing rates of evapotranspiration might amount to an additional 2-inch depth of water; hence, the total natural storage fluctuation ordinarily might be in the order of 5 inches of water. Assuming an average coefficient of storage of 0.1--a conservative estimate for the water-table aquifers of the Coastal Plain--the 5-inch change in storage would be reflected in an average water-table fluctuation of 50 inches--a small fraction of the saturated thickness of most water-table aquifers of the Coastal Plain.

Artificial Fluctuations

Man is able to provide additional ground-water storage by pumping water from the aquifers. In most places in areas of humid climate pumping increases the recharge to the aquifers by: (1) Lowering the water table and thus providing additional storage space for infiltration of precipitation that otherwise would have been rejected; and (2) by inducing infiltration from streams, lakes, or swamps where the normal hydraulic gradient toward these discharge areas is reversed. Pumping increases the total discharge, although it may reduce the evapotranspiration of ground water by lowering the water table and capillary fringe below the reach of plant roots and the capillary zone below easy reach of evaporation opportunity; additionally, pumping eventually reduces the discharge at other natural outlets by decreasing the hydraulic gradients toward those outlets. The local rate of recharge and discharge might then exceed by a substantial amount the estimated average rate of natural recharge and discharge of about 1.1 mgd per square mile of aquifer intake area.

Aquifer storage also could be used by recharging unfilled aquifers artificially with imported surface supplies. These supplies would augment the recharge induced from streams within the area. However, except for heavily pumped industrial and municipal well fields in which large withdrawals are concentrated in small areas, it is unlikely that imported supplies would be required.

CHEMICAL CHARACTER OF GROUND-WATER SUPPLIES

The waters of the Coastal Plain aquifers, except where contaminated by salt water, are generally of good quality and suitable for most uses. Usually they are of the calcium bicarbonate type, soft or only moderately hard, and are not highly mineralized. Many wells yield water free from objectionable quantities of iron, but in every aquifer localized objectionable concentrations of iron are found with an apparent random distribution, both areally and with depth. Treatment, if required, is usually limited to softening or the removal of iron.

Aquifers may be contaminated locally from surface sources, the disposal of wastes through recharge wells, leakage through corroded well casings, or from encroachment of salt water. In general, the waters from the several aquifers of the Coastal Plain do not differ greatly; they are described in the following sections and representative chemical analyses are given in table 5.

Pleistocene Deposits

Some of the best ground water in the Coastal Plain is obtained from the aquifers of the Pleistocene series, which comprise the shallowest (or uppermost) aquifers. The water is, for the most part, soft or only moderately hard. It contains relatively low concentrations of calcium and magnesium, and is only moderately mineralized. The dissolved-solids concentration is usually less than 200 ppm. The average hardness, as $CaCO_3$, determined by 41 analyses of water from the Pleistocene sediments in Delaware, was 51 ppm and it ranged from 7 to 248 ppm (Marine and Rasmussen, 1955, p. 85). The water from the Pleistocene sediments often contains excessive concentrations of iron. Occasional samples with high concentrations of nitrate, sulfate, hardness, or total dissolved solids (table 5) usually represent contamination from surface sources. The native water is generally satisfactory for most uses without further treatment except where the removal of iron is required. The principal discharge of ground water to the streams of Delaware and of a large part of coastal New Jersey is from the Pleistocene series; this is largely responsible for the good quality of water in many of the streams of the Coastal Plain.

Table 5.--Representative chemical analyses of ground water in C

(Concentrations in parts per m

Analysis no.	County and state	Depth (feet)	Date of collection	Temperature °F	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	So (
						Quaternary (Pleistocene) deposits				
1	Sussex, Del.	131;102	9-23-44	--	25	14	--	17	5.3	
2	New Castle, Del.	24-25	4-23-31	--	14	.03	--	11	8.1	
3	Salem. N. J.	242	1-11-51	55	9.7	4.8	0.00	14	2.3	
4	Burlington, N. J.	45	7-3-53	--	5.3	.20	.33	13	4.5	
5	Cape May, N. J.	50	10-17-56	--	12	.19	.01	14	1.8	--
6	Bucks, Pa.	35	2-28-56	--	12	.16	.00	21	8.8	--
						Cohansey sand				
7	Atlantic City, N. J.	64	8-13-57	57	6.2	.28	.00	0.8	.2	
8	Salem, N. J.	105	4-27-56	51	22	1.5	.05	2.3	.4	
9	Gloucester, N. J.	147	4-23-51	55	5.5	.01	.18	1.2	.8	
10	Burlington, N. J.	80	8-8-51	54	4.1	3.2	.09	.2	.7	
11	Burlington, N. J.	67	11-13-51	58	4.7	.00	.00	.5	.2	
						Kirkwood formation				
12	Sussex, Del.	242	12-28-51	--	55	.13	.01	48	6.9	
13	Kent, Del.	253	1-26-52	--	47	.16	--	31	6.4	--
14	Burlington, N. J.	350	8-14-51	56	26	.10	.00	.8	.9	
						Vincentown sand				
15	Kent, Del.	272	8-20-54	58	12	.25	--	33	9.8	
16	Salem, N. J.	156	4-26-56	53	12	.15	.00	36	12	
17	Salem, N. J.	133	12-21-50	--	36	1.9	.00	60	8.7	
						Wenonah and Mount Laure				
18	New Castle, Del.	164	8-20-54	--	16	.19	--	37	1.4	
19	Salem. N. J.	116	4-27-56	60	17	.26	.03	74	1.5	
20	Salem, N. J.	380	4-27-56	50	8.6	.33	.02	15	5.1	
21	Gloucester, N. J.	100	8-15-50	--	18	5.6	.00	34	1.2	
22	Burlington, N. J.	150	6-21-51	57	13	.28	.00	22	5.7	
						Englishtown sand				
23	Monmouth, N. J.	200	3-13-57	54	15	.62	.02	42	1.6	
24	Burlington, N. J.	260	3-22-51	56	27	.45	.10	43	4.0	
25	Monmouth, N. J.	480	3-1-57	58	12	.88	.01	38	3.2	
26	Monmouth, N. J.	657	8-8-51	54	13	.60		26	5.1	--
27	Ocean, N. J.	825	3-13-57	64	17	1.0	.14	20	5.5	
28	Ocean, N. J.	1,136	3-13-57	70	12	.19	.06	5.8	.6	
						Nonmarine Cretaceous				
29	New Castle, Del.	--	7-2-56	--	14	.01	--	4.7	2.7	--
30	Salem, N. J.	322	4-26-56	54	8.3	.11	.05	11	5.4	
31	Camden, N. J.	387	5-1-51	61	10	.11	.00	14	2.9	
32	Burlington, N. J.	57	7-3-53	--	9.4	.00	.19	12	10	
33	Burlington, N. J.	120-140	5-22-51	57	14	9.3	.00	16	5.2	
34	Mercer, N. J.	205	9-26-49	--	9.3	4.1	--	2.2	1.2	

TABLE 5

of ground water in Coastal Plain of Delaware River basin and New Jersey

ns in parts per million)

Cal- cium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Hardness as $CaCO_3$ Total	Hardness as $CaCO_3$ Non-carbonate	pH
ocene)	deposits											
.7	5.3	37	3.3	23	9.8	86	--	0.0	204	64	45	6.0
.1	8.1	18	1.2	20	40	27	--	15	146	61	41	
.4	2.3	90	4.0	131	25	74	0.5	.8	244	44	0	6.5
.3	4.5	3.8	1.8	40	24	4.2	.0	1.3	85	51	18	7.2
.4	1.8	--- 12 ---		31	12	16	.1	8.7	106	42	17	7.4
.1	8.8	--- 9.0 ---		53	48	8	.1	4.1	140	89	45	7.4
bansey	sand											
0.8	.2	1.6	.4	4	0.	2.6	.1	.4	20	3	0	6.3
2.3	.4	7.4	5.2	11	19	3.0	.2	1.2	61	9	0	6.0
1.2	.8	2.7	.4	5	1.0	4.2	.0	5.0	25	8	4	6.4
.2	.7	1.8	.3	7	0	2.9	0	.1	13	3.6	0	6.7
.5	.2	1.5	.3	14	2.0	2.8	.0	.2	22	2	0	6.5
irkwood	formation											
8	6.9	6.4	2.5	192	2.0	3.4	.1	.0	219	148	4	7.9
1	6.4	--- 23 ---		174	6.0	2.8	.2	.1	202	104	0	7.8
.8	.9	2.9	2.2	1	10	3.1	.0	.1	49	6	5	4.7
entown	sand											
3	9.8	9.9	9.0	80	4.7	2.5	.2	2.2	177	156	24	7.9
6	12	9.0	6.9	170	30	3.0	.3	.0	200	139	0	8.0
0	8.7	7.4	4.9	212	24	5.6	.4	.7	254	186	12	7.6
h and	Mount Laurel sands											
7	1.4	1.9	3.9	80	18	10	.1	.3	152	107	31	7.9
4	1.5	4.4	1.9	150	48	24	.2	.0	250	191	68	7.6
5	5.1	24	8.2	141	6.4	4.0	.3	1.2	155	59	0	8.2
4	1.2	2.2	2.8	83	20	5.9	.5	.2	133	90	22	7.6
2	5.7	5.3	8.5	111	5.0	2.0	.1	.0	115	78	0	8.1
htown	sand											
2	1.6	2.3	2.5	98	28	4.5	.1	.2	147	143	31	7.6
3	4.0	2.2	5.7	149	7.0	2.6	.4	.3	166	124	2	8.2
8	3.2	2.7	3.9	136	4.6	2.7	.1	.2	143	108	0	8.4
5	5.1	--- 7.0 ---		98	14	4.0	.1	.4	113	86	6	7.6
0	5.5	24	11	148	6.0	1.6	.2	1.0	163	73	0	7.8
5.8	.6	67	9.0	211	3.8	2.2	.1	1.6	210	17	0	8.6
arine	Cretaceous sediments											
.7	2.7	--- 7.2 ---		21	16	3.0	.1	.1	64	23	5.8	6.4
1	5.4	11	1.9	20	44	7.5	.2	.8	107	50	34	7.2
	2.9	21	6.3	103	15	1.8	.4	1.2	124	47	0	7.8
	10	10	3.6	34	40	12	.0	13	145	71	43	6.9
	5.2	2.7	4.3	64	16	2.1	.2	.3	86	61	9	7.1
.2	1.2	2.3	1.0	8	6.2	2.4	.1	.1	27	10	4	5.6

Source and description of samples referred to by number in table 5

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1. Rehoboth Beach, Sussex County, Del., Composite of 2 municipal wells.
2. New Castle, New Castle County, Del., Composite of 3 shallow municipal wells, New Castle Board of Water and Light Commission.
3. Pennsville, Salem County, N. J., Lower Penns Neck Water Department well, phosphate 0.4 ppm.
4. Beverly, Burlington County, N. J., Delaware River Water Co. well 2; aluminum 0.0 ppm, cooper 0.00 ppm, zinc 0.00 ppm, phosphate 0.0 ppm.
5. Rio Grande, Cape May County, N. J., Wildwood Pumping Station; color 2.
6. Levittown, Bucks County, Pa., Lower Bucks County Joint Municipal Authority; color 4.
7. Folsom, Atlantic County, N. J., P. Jacob well.
8. Parvin State Park, Salem County, N. J., State of New Jersey well; color 30, lithium 0.5 ppm.
9. Newfield, Gloucester County, N. J., Newfield Water Department well 2; phosphate 0.0 ppm, nitrite 0.00 ppm, color 5.
10. Lebanon State Forest, Burlington County, N. J., Pakin Pond Well, State of New Jersey; color 2, barium 0.0 ppm, aluminum 0.4 ppm, phosphate 0.0 ppm, nitrite 0.0 ppm.
11. Chatsworth, Burlington County, N. J., A. DeMarco well; color 3, aluminum 1.5 ppm, cooper 0.0, zinc 5.0 ppm, phosphate 0.0.
12. Milford, Sussex County, Del., Milford Water Department well, Frederica aquifer; color 2, zinc 0.0 ppm, phosphate 0.2 ppm, copper 0.0 ppm, turbidity 2.3 ppm.
13. Dover Air Base, Kent County, Del., U. S. Air Force well, Cheswold aquifer; color 2.
14. Harrisville, Burlington County, N. J., well.
15. Clayton, Kent County, Del., Clayton city well; color 8.
16. Alloway, Salem County, N. J., Williams General Store well; color 10, lithium 0.8 ppm.
17. Quinton, Salem County, N. J., Salem Water Co. well; color 6, phosphate 0.2 ppm, nitrite 0.00 ppm.
18. Odessa, New Castle County, Del., H. Davis well; Wenonah sand.
19. Woodstown, Salem County, N. J., Woodstown Restaurant well; color 20, lithium 0.2 ppm.
20. Dikes Mills, Salem County, N. J., Warren Cobb well; color 25, lithium 0.6 ppm.
21. Sewell, Gloucester County, N.J., James Ledan well; color 5, phosphate 0.1 ppm, nitrite 0.00 ppm.
22. Vincentown, Burlington County, N. J., Vincentown Water Co. well; color 8, aluminum 0.0 ppm, phosphate 0.0 ppm, nitrite 0.0 ppm.
23. Freehold, Monmouth County, N. J., Freehold Water Department, composite of 9 wells.

Source and description of samples referred to by number in table 5--
Continued

24. Marlton, Burlington County, N. J., Marlton Water Co. well; color 0, phosphate 0.3 ppm, nitrite 0.0 ppm.
25. Farmingdale, Monmouth County, N. J., Farmingdale Water Department well 1.
26. Belmar, Camp Evans, Monmouth County, N. J., U. S. Army Building 82
27. Point Pleasant, Ocean County, N. J., Point Pleasant Water Department well 1.
28. Lavalette, Ocean County, N. J., Lavalette Borough Water Department well 2.
29. Near Summit Bridge, New Castle County, Del., Near Chesapeake and Delaware Canal; Magothy.
30. Salem, Salem County, N. J., Salem Ice and Cold Storage well; color 10, lithium 0.2 ppm.
31. Blackwood, Camden County, N. J., Blackwood Water Co. well; color 2, aluminum 0.0 ppm, nitrite 0.0 ppm, phosphate 0.2 ppm.
32. Beverly, Burlington County, N. J., Delaware River Water Co. well 3; color 3, lithium 0.2 ppm, copper 0.00 ppm, zinc 0.00 ppm, phosphate 0.1 ppm.
33. Maple Shade, Burlington County, N. J., Maple Shade Township well; color 3, aluminum 0.0 ppm, phosphate 0.2 ppm, nitrite 0.0 ppm.
34. Hightstown, Mercer County, N. J., Hightstown Water Department well 1; color 12.

Cohansey Sand

The water from the Cohansey sand is generally the best obtained from the Coastal Plain aquifers (table 5). It is not highly mineralized and is soft. Some samples are moderately high in iron, and the water is generally slightly acid and corrosive to iron pipes and fixtures. Soluble materials in or near the surface may be dissolved by precipitation and (or) irrigation water, and affect the composition of the ground water locally. In this way the leaching of chemical and organic fertilizers yields above normal nitrate concentrations. Salt water has encroached into the Cohansey sand in a few places where extensive cones of depression have formed near salt-water bodies. There are few industries in the area that are underlain by Cohansey sand, therefore, at present the industrial use of water from the Cohansey sand is not great; the water is chiefly used on a large-scale basis for municipal supplies and for irrigation. The Cohansey sand is potentially the most productive aquifer in the New Jersey part of the Coastal Plain, but must be protected from contamination and salt-water encroachment if it is to continue to produce the high quality water it now yields.

Sands of the Kirkwood Formation

The Kirkwood formation yields soft water, generally of good quality, with a dissolved-solids concentration usually less than 250 ppm (table 5). The iron concentration is usually less than 0.3 ppm, but occasionally it is higher; commonly the silica concentration is 30 to 50 ppm. The water from some parts of the Kirkwood formation is slightly acid. The water is usually used without treatment; sometimes it is softened or the pH adjusted before use. Salt water has encroached in the aquifer in a few places near the seacoast.

Vincentown Sand

The Vincentown sand yields water that is hard and moderately high in dissolved solids (table 5). It is mildly alkaline on the pH scale and in places contains objectionable concentrations of iron. Near the Delaware River there is a possibility of salt-water encroachment, but a considerable thickness of silt and clay in the river channel at the outcrop area probably retards the interchange of water between the Vincentown sand and the river (Barksdale, Greenman, Lang, and others, 1958, p. 149). Water from the Vincentown sand is used for farm and domestic supplies and as a supplementary municipal supply for Salem, N. J.

Wenonah and Mount Laurel Sands

Water of good quality is obtained from the Wenonah and Mount Laurel sands (table 5). It is soft to moderately hard, with less than 150 ppm of dissolved solids, and is fairly uniform in chemical composition. It is suitable for most uses without treatment, although excessive amounts of iron occur in some parts of the aquifer and water from such parts must be treated to remove the iron.

Englishtown Sand

The Englishtown sand, like the Wenonah and Mount Laurel sands, yields water that is moderately hard (table 5). Normally the water is slightly alkaline and contains less than 200 ppm of dissolved minerals. It is suitable for most uses without treatment, although occasionally softening or the removal of iron is required. The Englishtown sand is less subject to salt-water encroachment than are the other Coastal Plain aquifers.

Nonmarine Sediments of Cretaceous Age

The uncontaminated waters from the nonmarine sediments of Cretaceous age are relatively low in dissolved-solids concentration (3-200 ppm), soft, and in general of high quality (table 5). Near the intake areas where the recharge consists chiefly of rainwater, the water is soft, slightly mineralized, slightly acid, and somewhat corrosive. As the water flows downgradient in the formation it becomes more mineralized, slightly alkaline, and noncorrosive and generally contains more iron, sometimes in objectionable quantities. The fluoride concentration is usually 0 to 0.1 ppm but in the vicinity of Woodstown and Glassboro, N. J., exceeds 1 ppm.

In several places the native waters are contaminated. The location of the interface between fresh and salt water is described on pages 16, 57, 59. Where withdrawals of water near the interface are large, the encroachment of salt water may occur. This is true in the vicinity of Salem and Woodstown, N. J. In the vicinity of Camden and Philadelphia, the Delaware River flows over the outcrop of the Raritan and Magothy formations. Here, where large quantities of water are withdrawn, the aquifers are recharged with river water, and the quality of the well water approaches that of river water. Above Camden the river water is no more mineralized than the native ground water, and river recharge has no adverse effects on, or may even improve, the quality of the well water. Dowstream from Camden, however, the river water is more highly mineralized and (or) polluted, and wells near the river have been, and more of them may be, adversely affected by induced recharge of such water.

The highest concentrations of dissolved solids in the lower aquifer of the Raritan formation are found within the city of Philadelphia. This arises from 3 principal sources: (1) The disposal of wastes on dumps on the intake area of the aquifer; (2) seepage from leaky sewers; and (3) wastes discarded into "sanitary" or "dry" wells.

SALT-WATER ENCROACHMENT

Salt-water encroachment has been defined in many ways. Here we shall define it as the encroachment on fresh-water domains of any saline water in concentrations and volumes large enough to be deleterious.

In parts of the United States salt-water encroachment may have as its source brines from oil wells; salty waste liquors (bitterns) left after refinement of table salt; bitterns developed in the production of magnesium and by-products from brines; mineralized waste waters from some mines; salt that has accumulated in improperly designed or

operated irrigation systems; "salt banks"--outcrops of salt deposits along stream courses; salt springs; salt domes; juvenile water; connate water; water from modern seas; and residual saline water left by the high-level Pleistocene seas.

In the Delaware River service area, fortunately, the sources of saline water are few and readily identifiable. Of the sources named above we need only concern ourselves with the last two, namely, modern sea water and residual salines.

The residual salines are, or may be, similar to connate water--water that was entrapped with sediments as they were being deposited in the sea--but the residual salines are of late marine origin and they gained entrance into aquifers and aquicludes during the interglacial ages when the land was flooded by high-level Ice Age seas. Most of the residual salines are now greatly modified from their original chemical condition; usually they have been diluted and have undergone ion exchange. This is a process by means of which calcium or magnesium in the water is exchanged for sodium, and to a lesser extent for potassium, in the enclosing rocks, or vice versa, depending upon local conditions.

With respect to location, residual saline bodies inland from the shore area most commonly occur in aquicludes where they are found in the least permeable parts. This is because Ice Age salt water has been flushed out of the permeable aquifers and the more permeable parts of the aquicludes in the time since the last high-level Ice age sea; but not enough time has elapsed for the slow, normal circulation through the deeper or less permeable sediments for flushing to take place.

Thus, where salt-water encroachment occurs in an area of the Coastal Plain it makes considerable difference if the source is a residual saline body or comes from the modern sea. In the latter case, the supply of salty water is unlimited and the maximum salinity is about 19,000 to 20,000 ppm in chloride content; in the former case the supply may be small--though not necessarily so; it all depends upon the volume of residual water being tapped--but in the Coastal Plain sediments in this area the salinity will never be as high as that of the ocean. It is highly important, therefore, that the source and kind of salty water causing the encroachment be identified early, for each of the two kinds of sources requires that a different developmental plan be used to prevent the ruin of the fresh-water aquifer being developed.

The density of water increases as the salinity increases. Pure water, which contains no dissolved solids, is a standard for measuring the specific gravity of liquids and is assigned a value of unity. Average ocean water contains approximately 35,000 ppm of dissolved solids (including about 19,000 ppm Cl) and has a specific gravity of 1.025. Thus fresh water is 40/41 as heavy as ocean water.

Average ocean water (Sverdrup, Johnson, and Fleming, 1946) contains the following principal constituents in parts per million: Calcium (Ca) 400; magnesium (Mg) 1,270; sodium (Na) 10,600; potassium (K) 380; bicarbonate (HCO_3) 140; sulfate (SO_4) 2,650; chloride (Cl) 19,000; total dissolved solids 34,500.

Inasmuch as ocean water is heavier and denser than fresh water, the 2 liquids tend to remain separate. Thus, where the 2 liquids are in contact, fresh water occupies a position above salt water and tends to remain there except as turbulence causes mixing.

In tidal reaches of streams and canals where salt water from the ocean has full access to the channels and where fresh-water flow is not sufficient to sweep the ocean water out, salty water commonly occupies the lower parts of the channels and extends inland as a blunt-nosed wedge. The seaward end of the wedge remains relatively unchanged at the ocean end of the channel, but the inland end of the wedge moves to and fro with the tides, and advances and retreats seasonally, as ocean level rises and falls and as streamflow responds to changes in rate of runoff.

In major tidal estuaries, such as the Delaware, the salt-water wedge commonly is ill-defined. River currents, tidal currents, waves, propeller wash from large ocean-going vessels, and rough and uneven channel bottom and banks--all tend to mix salt and fresh water. If we may characterize the relationships in the Delaware Estuary, about all we can say is that as a rule the saltiest water is at the bottom of the channel; that the deeper depressions in the river bottom generally contain "pockets" of water of higher salinity than adjacent higher parts of the channel floor; that horizontally across the channel the salinity generally is about the same at the same depth below the water surface; and that the freshest water is at and just below the surface.

"Salinity intrusion in the Delaware Estuary does not occur as a well-defined salt-water wedge such as is found in many estuaries. In most parts of the estuary within the limits of salinity intrusion, salinities from surface to bottom are essentially the same." (Waterways Experiment Station, 1956). Under conditions of low freshwater discharge the salinity increases sharply downstream from the

Delaware Memorial Bridge, although under flood conditions the chloride concentration at this point is as low as 30 ppm. Upstream from the Delaware Memorial Bridge the stream is usually well mixed and there is little change in concentration with depth. In 1950-55 the chloride concentration was less than 40 ppm for at least two-thirds of the time at Marcus Hook, Pa., and nine-tenths of the time at Camden, N. J. Only for 5 percent of the time did the chloride concentration exceed 1,000 ppm at Marcus Hook; it was greater than 100 ppm only 1 percent of the time at Camden (Cohen, 1957). The extent of salt-water intrusion in the estuary depends upon fresh-water discharge, which is now regulated, and sea level, which has been rising slowly for centuries but has risen more than 6 inches since 1930.

As with other tidal streams in permeable materials that carry salt water in their channels, the Delaware River has an elongate prism of saline water under and along that part of its course where salt water occupies the channel much of the time. Salt water from the channel, because of its greater density than fresh water, sinks down to the bottom of the permeable sediments (to the base of the aquifers beneath the stream) and fills them from bottom to top. If fresh-water discharge takes place from aquifer to river, as it does in most of the length of the estuary, the fresh water flows toward the salt-water prism that underlies the channel and moves upward over the prism to seep into the stream along its sides and shoreward bottom.

Where ground-water pumping begins in such an area and is great enough, or near enough the river's edge so that even small pumpage is effective, salt water from the prism beneath the stream migrates toward the wells, and the prism widens accordingly. Eventually the salt water reaches the wells. Restoring the fresh-water--salt-water contact to its original position may be a long and difficult task, or even impossible. At Lewes, Del., where salt water was drawn into the municipal well field from the Lewes-Rehoboth canal when pumping was greatly stepped up during World War II, the original well field had to be abandoned (Marine and Rasmussen, 1955, p. 138). New well supplies were quickly developed distant from the salt water of the canal and are being used to this day. In the meantime ground water in the old well field is freshening as recharge from precipitation flushes the salty water out of the aquifer. But the old well field is not safe for continued large-scale pumping again--if it were to be used heavily again salt water would encroach upon it.

The encroachment problem in the aquifers of the Delaware Estuary area has never been studied in detail as it has been in parts of Florida (Parker, 1955, p. 617-619) and Maryland (Bennett and Meyer, 1952, p. 154-157), although unpublished, local "spot studies" at and near certain well fields have been made, chiefly by consultants. Nonetheless, the principles involved are well known and apply to the Delaware River as well as to the Miami River and Canal, or to the Patapsco River estuary.

Many miles of coastline in Delaware, New Jersey, New York, and Connecticut, in the area of this report, are bounded by the ocean, or bays connected with the ocean. Generally, throughout this region, the shores are in areas of permeable materials such as unconsolidated sand and gravel of the Cretaceous and Tertiary periods, or glacial materials of the Pleistocene epoch. In materials such as these where salt water and fresh water come into contact, their relationship is largely governed by the Ghyben-Herzberg principle. This is the familiar rule that, since fresh water is 40/41 as heavy as salt water, it will take a body of fresh water 41 feet high to weigh as much as a similar body of salt water 40 feet high. Or, stating the rule another way, given 1 foot of fresh water above sea level, the salt water will be found 40 feet below sea level; given 2 feet of fresh water, the salt water would be 80 feet below sea level, and so on. On a freely permeable island surrounded by ocean water, the "lens" of fresh water in the island's rocks floats upon the surrounding and underlying ocean water much as an ice cube floats in a bowl of water, with most of its mass submerged.

However, the relationship between fresh water of the aquifers and salt water of the ocean or bay is not the simple static relationship of the ice cube to the bowl of water. The aquifer-ocean relationship is a dynamic situation and forces not considered in the Ghyben-Herzberg principle, which is simply that of the U-tube, operate. These forces have not been adequately defined to date but are the subject of a considerably amount of research, notably, in the United States, by the U. S. Geological Survey and the University of California. They are:

1. Molecular diffusion in the interface zone tends to dissipate the encroaching salt-water wedge.
2. Alternating tidal thrust and pull in and near the shore zone is a powerful mixing force in the aquifer, and it widens and thickens the zone between the fresh water and the salt water.
3. Fresh-water flow over the salt wedge exerts a slight downward pressure but its chief effect is an "eroding" force (Parker and others, 1955, p. 612) which sweeps seaward the tidally mixed and diffused salt water; this action is especially effective during the falling stage of the tidal cycle when the main body of the salt-water wedge not only moves seaward but also loses height throughout the area from which it withdraws.

Thus we cannot apply the Ghyben-Herzberg principle to salt-water encroachment problems without making due allowance for these named factors. However, it is certain that the 1-to-40 ratio of the Ghyben-Herzberg principle is a "safe" factor to apply in the development or conservation of water supplies in coastal aquifers, for seldom will equilibrium ever be reached, even close to the sea, at this limited

ratio. Rather, the depth to salt water will usually be greater than that predicted on a 1-to-40 ratio , and, likewise, the amount of inland encroachment of an intruding wedge of salt water will be somewhat less.

But even with this information, our control of salt-water encroachment demands rather complete knowledge of all the factors involved. These factors are the most important: (1) The geology of the aquifers and associated aquicludes; (2) the hydrologic constants of the aquifers, including the coefficients of transmissibility and storage; (3) the changing hydrologic factors, such as changes in storage, head, and migration of the salt-water--fresh-water interface.

Thus to evaluate and conserve the water resources we must be well informed of the local conditions under which the salt-water--fresh-water system operates. It is essential that an accounting system of "input and outgo" be maintained so that changes in storage can be known and, under given expected conditions of rainfall, runoff, recharge, evapotranspiration, pumping, and other related factors, predictions can be made of future availability of water. Such an evaluation and accounting are important anywhere in the basin and its service area, but in seacoast areas, or inland areas where saline sources exist that are potential sources of encroachment, every precaution must be taken to safeguard our water supplies.

On the basis of past experience, one might think that there is little to worry about for problems of salt-water encroachment have been faced before and have been solved, generally without excessive cost or irreparable damage. However, it would be most unwise to conclude that conditions will always be so easily handled, hence this note of warning so that precautionary measures may be taken in adequate time.

This logically leads to such pertinent questions as : "What is the salt-water encroachment situation in the basin and its service area today?"; "Where are the danger spots?"; and "What may we do to protect our fresh-water supplies against salt-water encroachment?"

General answers can be given to each of these questions, and for certain localities such as Atlantic City, Asbury Park, Philadelphia, Camden, Newark, and a few others, specific answers can be given. But, for the most of the rest of the basin, generalizations must suffice for now. This is because the essential data needed to supply specific answers for local areas generally are not available. Detailed local information, such as David G. Thompson and subsequent workers (Thompson, 1928; Barksdale and others, 1936) gathered for the Atlantic City area, N. J., are needed now all along the shores and inland as far as tidal streams carry salty water; and such detailed

data will be needed urgently over all the Coastal Plain of Delaware and New Jersey in the foreseeable future. Our understanding of the salt-water encroachment situation over a large reach in the area of the report probably is best developed at present on Long Island, N. Y., but even on Long Island there is still much detailed local information needed.

Within the Delaware River basin and the adjacent Coastal Plain parts of New Jersey and Delaware, salt-water encroachment is a most serious threat to shallow aquifers along the shores and the tidal reaches of streams that at times carry salty water. Thus the entire eastern shore of Delaware and that part of New Castle County that is bisected by the Chesapeake and Delaware Canal are potentially threatened by salt-water encroachment. Salty water at times extends up the Delaware River to Philadelphia, thus New Jersey is surrounded by salty-water boundaries from Philadelphia to Cape May and northward along the Atlantic Ocean to and somewhat beyond Newark. Because all the Coastal Plain is underlain by aquifers and aquicludes of varying permeability and hydraulic head, the opportunity for encroachment to spread inland varies accordingly.

Under the general operation of the Ghyben-Herzberg principle, with modifications imposed by dynamic conditions (p. 54), Nature has established interface zones in the several aquifers at different places with respect to the modern shoreline. Thus, in the nonmarine Cretaceous sediments, the salt-water--fresh-water interface (using 250 ppm as the bounding isochlor for the interface at depth in the aquifer) is along a gently curved line that crosses New Jersey diagonally from the ocean beach near Manasquan to a point on Delaware Bay about 8 miles south of Salem.' Salt water containing more than 250 ppm of chloride therefore underlies about half of the Coastal Plain in New Jersey in the nonmarine Cretaceous sediments, and pumping from deep wells tapping this aquifer group anywhere south and east of this line would yield only high-chloride water. Pumping from deep wells north and west of this line, and close to it--as in central Salem, Gloucester, Burlington, and Ocean Counties--would be likely to pull salt water inward--that is, to cause encroachment. No large-scale ground-water pumping would be safe in this region without careful prechecking to ascertain the status of the supply and the potential effects of the pumping on existing supplies.

The next major aquifer above the nonmarine Cretaceous sediments in New Jersey is the Kirkwood formation. This is the formation in which the "800-foot sand", utilized along the shore at Atlantic City and elsewhere, occurs. So far, there are only 2 areas of the Kirkwood along the ocean that yield water containing more than 250 ppm of chloride. The southernmost is the tip of Cape May peninsula, including all the area south of the Cape May Canal and northward to a line

extending about from North Cape May through Bennett to Wildwood. North of this line the hydraulic head in the Kirkwood generally has been sufficient to hold sea water some distance seaward from the present shore. Thompson (1928, p. 70-74) calculated that this salt-water--fresh-water interface in the Kirkwood was at least 7 miles offshore at Atlantic City at the time of his report.

The northern high-chloride zone in the Kirkwood formation is in the vicinity of Manasquan-Point Pleasant and extends inland only a couple of miles.

The westernmost high-chloride zone in the Kirkwood formation extends from Salem to Canton and southwestward almost to the mouth of the Cohansey River. Its average width, measured inland from Delaware Bay shore, is about 2 miles.

Pumping within any of these 3 zones in the Kirkwood formation would result in obtaining water containing more than 250 ppm of chloride; and pumping inland from these areas, especially near the salt-water boundaries, would induce encroachment.

The next important aquifer, or aquifer group, above the Kirkwood formation is the Cohansey sand. This is the formation that, in the Atlantic City area, contains the "100-foot" and the "200-foot" sands (Barksdale and others, 1936, p. 52-91). For the sake of convenience, aquifers in the overlying Pleistocene deposits are here grouped with the Cohansey.

Chloride in excess of 250 ppm occurs in the Cohansey sand along most of the New Jersey and Delaware coastline, beginning about at Point Pleasant Beach, in northeastern Ocean County, and continuing southward beneath the offshore bars and islands; and on the mainland beginning about at Toms River and continuing southward beyond Stone Harbor. In general, the inland margin of this salty zone follows fairly closely the line of U. S. Highway 9; the salt-water boundary bends inland in large curves around Great Bay and Great Egg Harbor, and between these places probably averages about 5 miles inland from the ocean shore. A tiny tip of the zone of water containing chloride exceeding 250 ppm exists in the Cohansey on Cape May, and a narrow strip borders Delaware Bay in New Jersey, usually less than a mile wide, as far as the mouth of the Cohansey River. In Delaware, on the opposite shore of Delaware Bay, a similar but generally wider strip extends almost to Cape Henlopen, including Lewes. South of Lewes the next area of high chloride (i. e. greater than 250 ppm) is at Rehoboth Beach; the southernmost areas surround Rehoboth Bay, Indian River Bay, and Assawoman Bay--the latter chiefly in Maryland.

Wells developed in the Cohansey sand--or in the permeable sands overlying it--in the areas described would thus yield only water containing more than 250 ppm Cl. If pumping were on a very large scale the salinity would undoubtedly increase as water of higher salinity was drawn into the aquifer. Inland from the zones described, wells should be developed with caution, not only because of danger to the new wells but also because existing supplies might be ruined by additional pumping.

Inland, from each of the zones of high chloride described above for the 3 principal aquifers or aquifer groups of the Coastal Plain, there is a zone of ground water containing chloride ranging from 250 ppm down to "normal". The word "normal" is put in quotes because not enough is known about the salt-water situation in this region to be certain of how much chloride should be considered "normal". Most ground-water hydrologists in New Jersey use 10 ppm for the norm, but Delaware ground-water hydrologists use 25 ppm in that State. Thus, mapping of chlorides in these ranges of values does not correlate from State to State.

If one uses 10 ppm as the "normal", then wide areas in western Salem and Gloucester Counties, N. J., are underlain by the intermediate belt of 10-250 ppm chloride in the nonmarine Cretaceous sediments. From this wide strip in Gloucester County a narrow band ½ mile to 3 miles wide, averaging perhaps 1 mile, extends all the way up the river as far as the head of tidewater, below Trenton; and a similar but wider strip occurs on the Pennsylvania side of the river.

Much of this chloride in the strip up either side of the Delaware River is, however, not derived from sea-water contamination. Most of it north of the Schuylkill River stems from industrial and municipal wastes derived from leaky sewers, so-called "sanitary" land fill, wastes disposed of through wells or septic tanks, and other human causes. As a matter of fact, the shallow aquifer in South Philadelphia, especially in the vicinity of the U. S. Navy Yard, and reaching under the river across to Camden, is rapidly becoming useless for most purposes except cooling.

But to get back to naturally occurring waters of salinity in the range from 10-250 ppm in the nonmarine Cretaceous sediments: there is a narrow ribbon of such water about a mile wide, extending from the very wide zone in Gloucester County, described above, northeast about to Manasquan. In Delaware, along the Christina River and Brandywine Creek and underlying most of Wilmington, a zone of such saline water occurs; another, much smaller, underlies Newark; and a third, about the size of that at Wilmington, underlies Delaware City.

In the Kirkwood formation most of Cape May County is underlain by water in the 10-250 ppm range. The southern boundary is, of course, the high-chloride zone previously described. The inland boundary of this 10-250 ppm zone extends northeastward about from Reeds Beach to Strathmore. In Delaware a fairly large area containing water of this quality extends from Delaware Bay at Liston Point downstream about 20 miles to Pickering Beach, and curves inland a maximum of about 10 miles to include Smyrna, Cheswold, and Dover.

In the Cohansey sand and hydraulically connected overlying Pleistocene deposits, practically all of Cape May County is included in this 10-250 ppm zone--excluding only those parts previously described where higher chloride exists, and a part of the northern end of the county where chloride is less than 10 ppm. Narrow strips a mile or so wide, usually a little less, border the higher chloride zone previously described, and extend generally northward along the route of U. S. Highway 9 as far as Toms River and northwestward in Cumberland County about to the Cohansey River. On the Delaware State side of the estuary this zone, about a mile or a little more wide, begins at the north near Wilmington; it borders the river about as far as Woodland Beach (east of Smyrna) and from this point south lies inland from the zone of high chloride preciously described. A few miles north of Lewes this zone widens greatly to almost parallel the shore in the reach from Cape Henlopen to the Maryland line. In this reach the inland margin of the 10-250 ppm zone averages about 10 miles west of the Atlantic Ocean.

This about sums up our present knowledge of the status of salt water in the Coastal Plain. Perhaps a few remarks about the situation in the vicinity of Newark, N. J., would not be amiss at this point.

Newark is in the Passaic River valley, lying just west of Newark Bay, a salt-water body that is connected both to New York Bay and to Raritan Bay by channels at the north and south ends of Staten Island.

The area is a part of the Triassic Lowland and is underlain by bedrock of the Newark group (p. 85-90) chiefly dense red shale and sandstone of the Brunswick formation of Triassic age. Prior to Pleistocene time a major valley developed, trending northeast with depths as great as 100 feet under Newark and dipping to 300 feet or more under Harrison. In Pleistocene time this valley and its tributaries were filled with glacial deposits of sand, gravel, silt, and clay. Modern streams developed after the Wisconsin ice sheet withdrew. Recent alluvium, chiefly silt, clay, and very fine sand, has accumulated over the glacial deposits, chiefly in and near present river beds. Thus in this part of New Jersey, the typical thick wedge of Cretaceous and Tertiary deposits, present in the Coastal Plain farther south, is entirely missing.

Water occurs in the Brunswick formation chiefly in its cracks and crevices. Herpers and Barksdale (1951, p. 27) estimated the specific yield of the upper 300 feet of these rocks to be about 1 or 2 percent. Water moves most readily through the more vertical cracks and especially through those trending northeasterly--apparently the joint pattern that produced the widest cracks.

The Pleistocene gravels and sands that overlie the Brunswick formation in the river valleys of the Newark area are relatively high in permeability and both transmit and store comparatively large quantities of water. The alluvium has a low or very low permeability, and where thick and compact is relatively impermeable; however, the alluvium is not everywhere thick and compact, therefore it acts as an imperfect aquiclude.

In the early days fresh water was obtainable from wells almost anywhere in the Newark area, except very near the river and bay, but heavy pumping in areas close to Newark Bay and the Passaic River, together with dredging of ship channels in these bodies, has caused salt-water encroachment to take place. The dredging was no doubt a prime contributor to encroachment by breaching the imperfect seal of Recent and, in some places, Pleistocene silt and clay (Herpers and Barksdale, 1951, p. 50), thus exposing the permeable sands and gravels directly to salt water throughout the entire length and depth of the excavations. This is a case that should be given careful consideration in regard to the proposed deepening of the ship channel in the Delaware Bay and River.

Salt-water encroachment "trouble spots" now exist in those coastal parts of the service area where large-scale pumping exists adjacent to salt-water bodies. Included are places that have already experienced the loss of once usable wells or well fields; others are potentially threatened with encroachment. Among them are Newark, Perth Amboy, South Amboy, Sayreville, Asbury Park, Atlantic City, Cape May, Penns Grove--all in New Jersey, and in Delaware the most threatened spots probably are Lewes and Rehoboth Beach. But, as mentioned earlier in this section, wherever new large-scale pumping is developed in an aquifer near the salt-water--fresh-water interface--as in the nonmarine sediments of Cretaceous aquifer in eastern Camden County, 60 miles or so inland from the ocean--salt-water encroachment could be induced and a new "trouble spot" could develop.

How may the fresh-water supplies be best protected against damage or ruin by salt-water encroachment? The answer is not a simple one because the problems themselves are complex. In general we must first of all develop a better understanding of local conditions in all aquifers and related surface-water bodies that have a bearing on the salt-water problem. We need comprehensive information for the whole Coastal Plain similar to, but even more detailed than, that now

available for the Atlantic City area--details on the local geology and hydrology such as depth, thickness, and effectiveness of aquifers and aquicludes; the hydraulic heads and water-table or piezometric maps depicting these hydraulic heads; the variation of chloride in the aquifers, with isochlor maps currently constructed at reasonable time-intervals, perhaps semiannually in some areas and annually in others; and other similar or related data, including changes of chloride and of stage and flow of surface-water bodies.

Given such essential background data consisting of permanent (geologic, chiefly) and changing (hydrologic and chemical quality) data, local or State authorities would be in a position to enact and put into effect the immediate controls required.

With respect to streams carrying salt water, the most effective way to keep salt water out is to utilize dams, tidal gates, or other barriers as far downstream as possible. Where water traffic is important, as it is on the Delaware and Passaic Rivers, such structures may be considered impractical because of navigational needs. If they are impractical, then the only alternative means of keeping salt water out of the streams is to maintain such high flows of fresh water that salt water cannot encroach in the face of it.

Salt-water encroachment may be hastened, or even initiated, by construction of a tidal canal or canal system designed to do no more than drain low-lying marshes. This was the prime cause of the serious salt-water encroachment problem in southeastern Florida (Parker and others, 1955, p. 584-591). Or the encroachment may stem from the breaching of a relatively impermeable blanket of silt and clay on the bed of a river when ship-channel dredging takes place (Herpers and Barksdale, 1951, p. 40). Thus, there is a real possibility of such encroachment in the lower basin, owing to the proposed additional deepening and widening of the ship channel from below Philadelphia to head of tidewater at Trenton.

Such dredging would undoubtedly facilitate the movement of water from the river into the aquifers, or vice versa, according to the relative hydraulic heads. No harmful results could accrue--in fact benefits would result--from such dredging if the quality of the river water were to be maintained in a satisfactory condition. But if the deepened and widened channel becomes an inland extension of the sea, or if pollutants are allowed to spoil the river water, the deepened channel would provide easy avenues of entrance to the aquifers, and the ground-water supplies would be endangered, if not ruined, for most uses.

One other effect to be expected from widening and deepening the cut through the aquifers in the Philadelphia-Trenton area is concerned with discharge from the aquifers. Removal of silt and mud on the river bottom would increase the discharge for any given head that exists in the aquifers above river level. This would result not only in reducing hydraulic head close to the river, but also in making it that much easier for salty or polluted water to move into the aquifer against the lowered fresh-water head in the aquifers.

No easy solution to this problem presents itself. It would be extremely costly and difficult to "pave" the deepened channel either by over-dredging and then allowing Nature to replace the removed silt-clay blanket, or to use cement grout or other known impermeable materials. The only practical ways are those mentioned earlier: (1) Construction and operation of a salt-water barrier or; (2) increased fresh-water flow in the river.

PRODUCTIVITY OF AQUIFERS

The productivity of an aquifer depends on several factors among which are the extent, thickness, average permeability, recharge potential, storage capacity, and susceptibility to salt-water encroachment of the aquifer. An approximate measure of the productivity of the aquifers in the Coastal Plain is provided by the expected yields of properly constructed drilled wells tapping the entire thickness of the aquifers. The location, spacing, and size of such wells depend on the factors mentioned above, and also on the economics of water demand. As discussed in the section on ground-water storage, the average rate of consumptive withdrawal--the net discharge from the aquifers--cannot exceed the average rate of recharge without depleting the storage and ultimately ruining the coastal portions of the aquifers by causing encroachment of salt water.

The hydraulic coefficients of, and yields of wells in, the aquifers of the Coastal Plain have been cited in a previous section. Plate 9 shows: (1) The areas in which it is known or believed that adequate wells can be developed in each aquifer; and (2) the productivity that may be expected from properly constructed modern wells penetrating the entire aquifer. The map is generalized and is based partly on interpolation and extrapolation of field data. Because the available data are not sufficiently comprehensive, the map (pl. 9) can only approximately represent the entire picture. For example, wells may not everywhere produce as much as the map indicates, especially on the fringes of the several areas; or highly productive zones may well extend beyond the boundaries shown, especially in a seaward direction.

THE APPALACHIAN HIGHLANDS

GENERAL FEATURES

The extensive region north of the Fall Line is a part of the Appalachian Highlands--a major physiographic subdivision of the United States (Fenneman, 1938). The region comprises parts of four physiographic provinces, each having distinctive landforms which are related to the types and structure of the rocks and to the geologic history of the province. From the Fall Line northward these include the Piedmont, New England, Valley and Ridge, and Appalachian Plateaus provinces (pl. 3). Each province is further subdivided into sections or subprovinces.

The Piedmont province contains 2 very distinct subprovinces: the Piedmont Upland, a considerably eroded low plateau formed primarily by weathered crystalline rocks such as granite, gneiss, and schist; and the Piedmont or Triassic Lowland, a lower and less rugged area formed largely by relatively soft shale and sandstone but including also ridges, hills, and small plateau-like surfaces formed by harder rocks--principally diabase, basalt, and argillite. Another, much smaller, area is Chester Valley (pl. 3), a narrow lowland trending westward across the center of the Piedmont Upland. Chester Valley is underlain by limestone and dolomite (carbonate rocks on pl. 11) which are soluble and therefore less resistant to erosion than the surrounding rocks.

The New England province extends into the basin from the northeast as a long tongue terminating near Reading, Pa. Within the basin it consists entirely of the Reading prong of the New England Upland subprovince which is called the Highlands in New Jersey. The area is moderately rugged and, especially in its northeastern part, it is characterized by approximately parallel, somewhat irregular ridges and intervening valleys all trending northeast. The ridges, which rise about 500-1,000 feet above the valleys, are formed largely by gneiss and related hard crystalline rocks; the valleys are underlain by weaker rocks--principally carbonate rocks and shale. Most of the New England province has been glaciated. In the northeastern part, in New Jersey, the ridges are blanketed by extensive deposits of glacial till, and the valleys contain thicker deposits--largely outwash--which completely mask the bedrock in most places.

The Valley and Ridge province is divided by a ridge known in Pennsylvania as Blue Mountain, into two main parts: (1)The Great Valley to the south; and (2) a sequence of narrow valleys and ridges to the north. Known also in New Jersey as Kittatinny Mountains, and in New York as Shawangunk Mountains, this ridge for convenience will hereinafter generally be designated as the Blue Mountain ridge.

The Great Valley, a relatively broad feature 8-20 miles wide in the basin, actually consists of 2 belts of contrasting landforms. The southern, and narrower, belt is a gentle lowland formed by relatively weak carbonate rocks. The northern belt, formed by more resistant shale, slate, and sandstone, is a deeply eroded surface rising abruptly several hundred feet above the lowland to the south. As in the New England province, the northeastern part of the Great Valley has been glaciated, and parts of this area are covered by glacial deposits of varying thickness and permeability.

North of the Blue Mountain ridge, the Valley and Ridge province is characterized by alternating ridges and valleys which trend generally northeast, parallel to the regional "grain" of the topography but which at many places curve, bend abruptly, reverse direction, or zig-zag. The highest and steepest ridges, which have rather uniform summit altitudes of 1,500-2,000 feet, are formed by the hardest materials--chiefly thick-bedded quartzose sandstone and conglomerate. Lesser ridges are formed by more thinly layered sandstone and hard shale. The valleys are underlain by rocks less resistant to erosion, such as soft shale and carbonate rocks.

The most extensive development of these valleys and ridges is west of the Lehigh River; the belt narrows between the Lehigh River and the Delaware Water Gap near Stroudsburg, Pa. Northeast of Stroudsburg the belt narrows still further and consists principally of the Kittatinny-Shawangunk Mountains ridge and the valley of the Delaware River. The area northeast of Stroudsburg has been glaciated, and the valleys of the Delaware River and its major tributaries are filled with glacial outwash.

The Appalachian Plateaus province, which occupies approximately the northern third of the basin, is an upland formed by flat-lying to very gently folded beds of sandstone, shale, and conglomerate. The gentle to flat structure of the beds contrasts with the strongly folded and faulted structure of the similar beds in the adjoining Valley and Ridge province and accounts for the difference in landform between the 2 provinces. The relation of rock structure to topography is well shown by the gradational change from one province to the other near the Lehigh River; there the folds in the Valley and Ridge province flatten toward the northeast gradually rather than abruptly.

The 2 sections or subprovinces of the Appalachian Plateaus province in the basin--the southern New York section (which includes the Pocono Mountains) and the Catskill Mountains--differ chiefly in relief; the boundary between them shown on plate 3 is vague and arbitrary. In both areas the layers of rock are nearly flat; the greater altitude and relief of the Catskills, which attain an altitude of 4,200 feet at Slide Mountain on the eastern border of the basin, is due to

the superior resistance to erosion of the conglomerate and coarse-grained sandstone, which are more abundant there. Few summits exceed 2,000 feet in altitude in the southern New York section of the plateaus, and most of the area is between altitudes of 1,000 and 1,500 feet. The Delaware River and its major tributaries have carved deep, narrow valleys across the plateaus in both subprovinces.

Probably all the plateau region has been glaciated, although the most recent glaciation--that of the Wisconsin stage (table 1)--did not extend into the southernmost part of the region (pl. 3). Glacial till mantles most of the area, and the drainage pattern has been modified greatly by the effects of the ice sheets. Marshes and lakes dot the flatter parts of the plateaus in Pennsylvania. The large valleys are filled with thick outwash.

OCCURRENCE OF GROUND WATER

In the Appalachian Highlands, ground water occurs in both consolidated rocks and unconsolidated sediments, but although the glacial outwash supplies the most productive wells, by far the most water is in the consolidated rocks because of their greater extent.

The glaciated northern half of the area is blanketed discontinuously by unconsolidated sediments. Thin unbedded deposits of glacial till lie on the interstream areas; bedded deposits of glacial outwash lie along the major stream valleys, both in the glaciated area and in the unglaciated area to the south. The glacial outwash is the most permeable and productive aquifer in the Highlands, but its total volume is small; nonetheless, if large local supplies of ground water are to be developed, the best sites for such developments would be where the larger bodies of glacial outwash are to be found in hydraulic connection with perennial streams, as is commonly the case in the larger stream valleys. Though much more extensive than the outwash, the glacial till is less permeable and usually is too thin to yield large perennial supplies of ground water.

The consolidated rocks underlie all the unconsolidated sediments and are exposed at or near the land surface throughout most of the southern, unglaciated, part of the Appalachian Highlands. The capacity of the consolidated rocks to store and transmit water ordinarily is much less than that of the unconsolidated sediments, but their great thickness and extent make the consolidated rocks the principal aquifers in the Appalachian Highlands.

The consolidated rocks are herein divided into 3 major categories based on the nature and distribution of their water-bearing openings: (1) Crystalline rocks; (2) carbonate rocks; and (3) clastic rocks. The general characteristics of each of these categories are described

briefly, and the geologic formations that compose each type are listed in the sections following. The individual formations are described very briefly in table 1, which shows also their relative ages and stratigraphic sequence. Because it is impossible to show in one table all the consolidated-rock formations in so large and diverse an area as the Appalachian Highlands portion of the Delaware River basin, table 6 lists the formations in each of the physiographic subdivision of the Appalachian Highlands and indicates their approximate age relations.

The outcrops of the consolidated-rock formations are shown on plates 11 and 12 and stratigraphic and structural relations of the rocks are in part shown diagrammatically on plate 13.

The unconsolidated sediments are described in a later section. Their extent is shown on plate 14 and their thickness and distribution in and adjacent to the major stream valleys are shown on plate 15.

CRYSTALLINE ROCKS

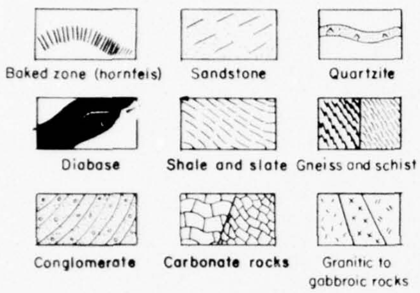
Crystalline rocks are composed of interlocking mineral grains--crystals--which formed either: (1) by cooling of molten material (to form igneous rocks) or; (2) by crystallization of previously existing rocks either through tremendous pressure as the earth's crust folded and was squeezed, or (and) by deep-seated emanations of hot liquids or gases to form metamorphic rocks. The crystals may range in size from microscopic grains to giants several inches in diameter.

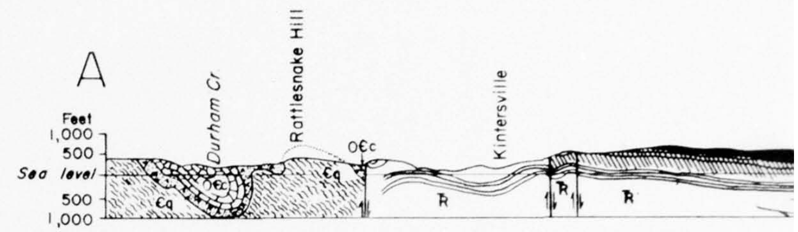
The common igneous rocks in the basin are granite, gabbro, diabase, and basalt. Of these, the granitic to gabbroic rocks cooled slowly at considerable depth in the earth's crust and are relatively coarse grained. Many of these rocks appear to be of igneous origin but are now believed to be actually of metamorphic origin. Diabase, a dark rock generally having smaller crystals than granite or gabbro, forms intrusive sheets (sills) and dikes in sedimentary rocks, whereas basalt, a still finer grained rock, originated as lava flows that became interbedded with sedimentary rocks.

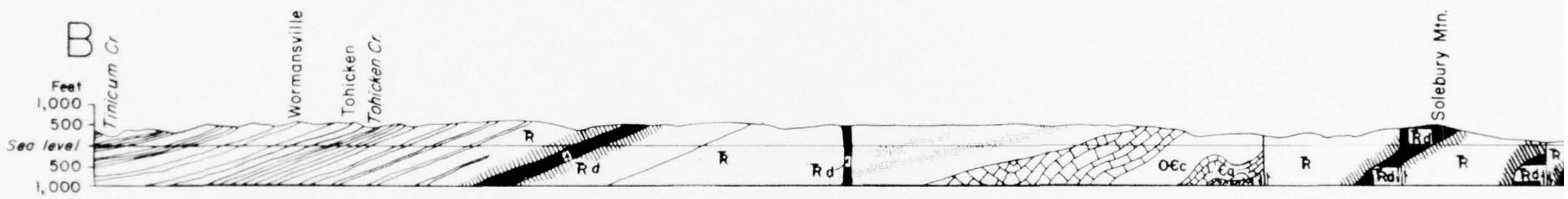
The metamorphic rocks of the Appalachian Highlands include gneiss, schist, phyllite, slate, quartzite, and probably some of the granitic-rock types mentioned above. These rocks derive their type name from the fact that they have been metamorphosed (changed) by heat and (or) pressure from rocks of sedimentary or igneous origin. They commonly have a pronounced banding, layering, or alinement of minerals.

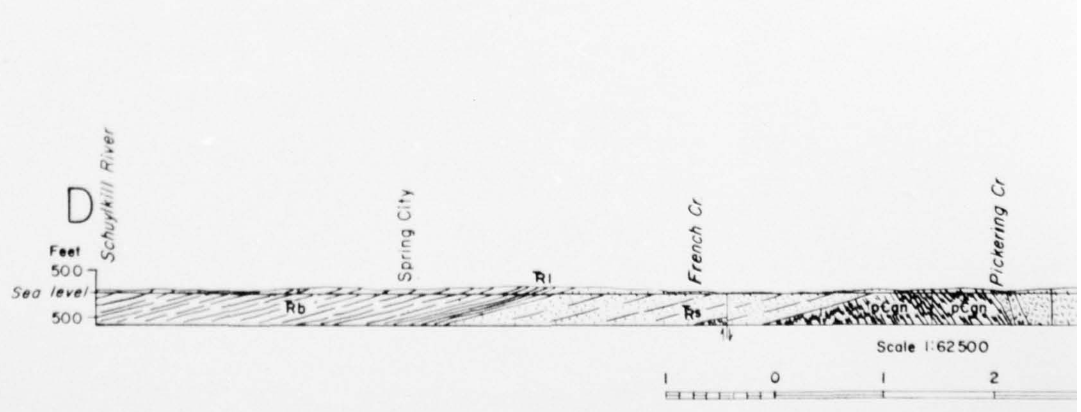
U.S. GEOLOGICAL SURVEY

EXPLANATION
OF
ROCK SYMBOLS
(Formational symbols
explained on plate 12



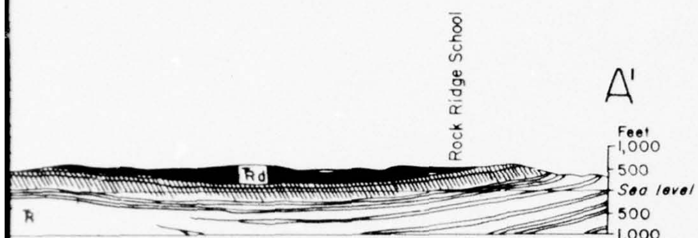




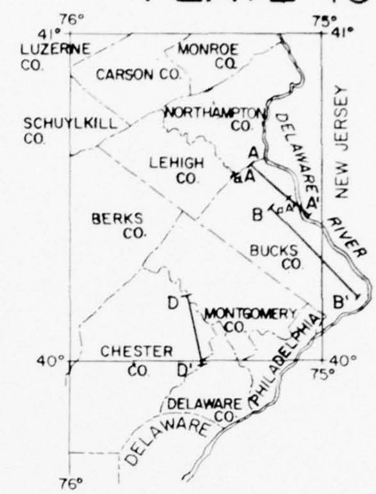


GENERALIZED GEOLOGIC CROSS SECT
OF APPALACHIAN H

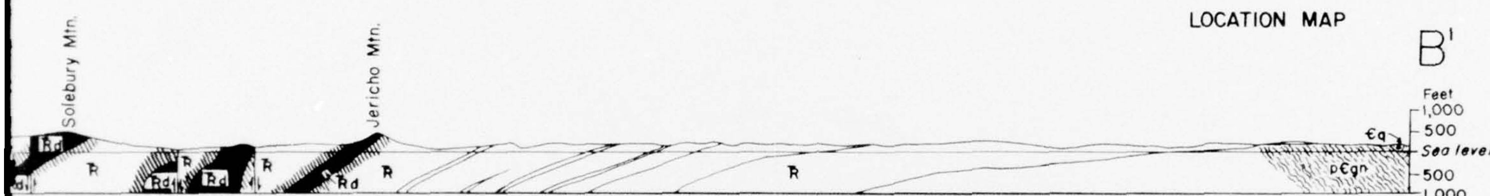
PLATE 13



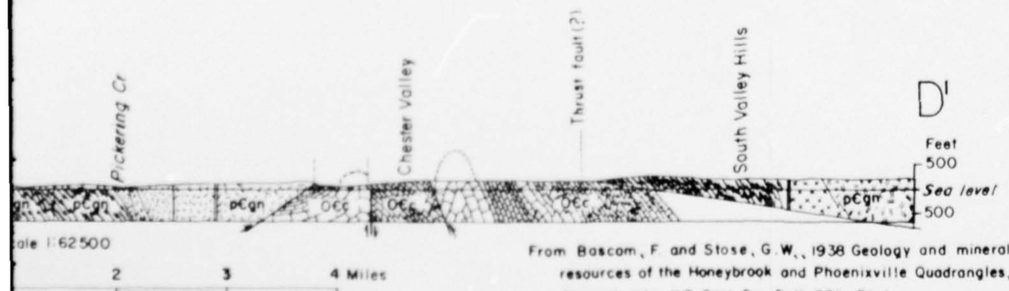
From Greenman, D.W., 1955, Ground Water Resources of Bucks County, Pa. Geol. Sur. Bull. W-11, Pl. 1.



LOCATION MAP



From Greenman, D.W., 1955, Ground Water Resources of Bucks County, Pa. Geol. Sur. Bull. W-11, pl. 1.



From Bascom, F. and Stose, G.W., 1938 Geology and mineral resources of the Honeybrook and Phoenixville Quadrangles, Pennsylvania, U.S. Geol. Sur. Bull. 891, Pl. 1.

S SECTIONS OF SOUTHERN PART
HIAN HIGHLANDS

These cross sections are presented only to show the general nature of the geologic structure. In some cases the structural interpretations differ from those shown on the geologic maps (pls 11 and 12). The cross sections are preliminary and subject to review, and have not been reviewed for conformance with stratigraphic nomenclature of the U.S. Geological Survey.

Some of the crystalline rocks grade imperceptibly into the other major types, so that any classification is arbitrary. For example, marble--a crystalline carbonate rock originating as a sedimentary rock (limestone)--has water-bearing properties similar to those of the non-crystalline carbonate rocks and for that reason is grouped herein with the carbonate rocks rather than with the crystalline rocks. Slate--a metamorphosed shale--grades into shale in parts of the service area and is grouped more conveniently with the clastic rocks than with the crystalline rocks. Some quartzite differs very little from hard, strongly cemented quartzose sandstone and conglomerate, and also may be grouped with the clastic rocks.

As defined herein, the crystalline rocks include the following units shown on plates 11 and 12 and listed in table 1.

Age	Map unit	Formation
Triassic	Diabase Basalt	"trap rock"
Cambrian	Quartzose rocks	Antietam sandstone Harpers schist Chickies or Hardyston quartzite
Early Paleozoic(?)	Glenarm series	Peters Creek schist Wissahickon formation Setters formation
Precambrian and Paleozoic	Granitic to gabbroic rocks Ultramafic rocks	
Precambrian	Gneiss	

Gneiss of Precambrian Age

The oldest rocks in the Delaware River basin are various types of gneiss and similar crystalline rocks of Precambrian age. They occur in both the major areas of crystalline rocks--the Piedmont Upland and the New England Upland--but are most extensive in the New England Upland.

The gneiss and related rocks are of diverse origin; they include highly metamorphosed sedimentary and igneous rocks, unmetamorphosed igneous rocks, and complex mixtures of these types. In the Piedmont

Upland many of the igneous or igneous-appearing rocks have been differentiatied from the known metamorphic rocks and are shown on the geologic map (pl. 11) as ultramafic rocks and granitic to gabbroic rocks, but in the New England Upland all the rocks are grouped as gneiss and related crystalline rocks (pls. 11 and 12).

In the Piedmont Upland the gneiss of known Precambrian age has been called the Baltimore gneiss and the Pickering gneiss. In the New England Upland the named formations include the Byram granite gneiss, the Lossee diorite gneiss, and the Pochuck gabbro gneiss, but there are also several kinds of unnamed gneiss believed to be largely of metasedimentary origin (Smith, 1957, p. 71-76). Because of their similar water-bearing properties, their uncertain correlation, and their complex associations, all these rocks are herein grouped in one hydrologic unit.

Most of the gneiss is medium to coarse grained and has a more or less prominent banding or layering of the minerals. In composition, the types range from light-colored rocks having abundant quartz and feldspar to dark rocks containing abundant iron- and magnesium-bearing minerals. Gneiss or schist containing graphite occurs at scattered localities in the Piedmont Upland.

Ultramafic Rocks

The ultramafic rocks (rocks high in magnesium and iron-bearing minerals) which consist of more or less altered or metamorphosed igneous rocks--chiefly serpentine, metapyroxenite, and metaperiodotite--occur as small masses at scattered localities in the Piedmont Upland. The outcrops form low hills and ridges that are distinctively barren of vegetation and are characterized by very thin soils. The small amount of water that occurs in these rocks generally has a high content of magnesium bicarbonate, owing to the abundance of magnesium in the rock-forming minerals.

Granitic to Gabbroic Rocks

The granitic to gabbroic rocks comprise granite, quartz monzonite, granodiorite, quartz diorite, syenite, diorite, anorthosite, gabbro, and related rocks. At many places these rocks intergrade with gneiss of Precambrian age or with schist and gneiss of the Glenarm series, so that it is difficult to portray the boundaries of the units on a geologic map. Only the larger masses of relatively unmixed granitic to gabbroic rocks in the Piedmont Upland are shown on the geologic map (pl. 11); in the New England Upland these rocks are grouped with the gneiss of Precambrian age.

Gabbro is the most abundant type in the southern part of the Piedmont Upland, whereas quartz monzonite, granodiorite, quartz diorite, and anorthosite predominate in the northern part of the Upland, north of Chester Valley. Most of these rocks are medium to coarse grained and are not as strongly banded or layered as the gneiss and schist. Fractures (joints) are relatively far apart, are regularly spaced, and commonly form a set of three mutually perpendicular planes. A set of curved fractures (sheeting) approximately parallel to the land surface is developed in some of the sparsely jointed rocks.

Like the other crystalline rocks, the granitic to gabbroic rocks contain dikes of pegmatite and metadiabase and veins of quartz. Many of these veins and dikes are highly fractured and yield more water than the surrounding rocks.

Glenarm Series

Most of the Piedmont Upland south of Chester Valley is underlain by a sequence of schistose and gneissose rocks of predominantly metasedimentary origin known as the Glenarm series (Bascom, Clark, Darton, and others, 1909, p. 4). In order of decreasing age the Glenarm series consists of the Setters formation, the Cockeysville marble, the Wissahickon formation, and the Peters Creek schist. The age of these rocks, formerly thought to be Precambrian, is now considered probably early Paleozoic. Increasing evidence indicates that the Glenarm series consists of more highly metamorphosed equivalents of rocks of known Cambrian and Ordovician age farther north (Watson, 1957), as shown in table 6.

The Setters formation consists largely of quartzite and mica-quartz schist and is similar to the Chickies quartzite of Cambrian age to the north.

The Wissahickon formation, which constitutes the bulk of the Glenarm series in the Delaware River basin, includes a variety of rocks ranging from gneiss in the southern part of the area to fine-grained schist and phyllite in the northern part. Micas (muscovite and biotite) are the most abundant minerals; other important minerals include feldspar, quartz, chlorite, and garnet.

The Peters Creek schist, which lies in the northern part of the outcrop of the Glenarm series, is generally similar to the fine-grained mica schist and phyllite in the Wissahickon formation immediately south.

Spacing and orientation of fractures in the rocks of the Glenarm series are dependent on the texture of the rocks and the direction of application of deformational forces in the earth's crust. Where mica or chlorite are abundant the rock tends to split readily, parallel to the layering of these minerals, but fractures are farther apart and more evenly spaced in the more massive rocks, where a considerable amount of admixed granitic or gabbroic rock is present.

Quartzose Rocks of Cambrian Age

The quartzose rocks of Cambrian age include the Chickies quartzite, the Harpers schist, and the Antietam sandstone in the Piedmont Upland, and their approximate equivalent, the Hardyston quartzite in the New England Upland (tables 1 and 6). These rocks actually are intermediate in character between the crystalline rocks and the clastic rocks; they consist of quartzose sandstone and some conglomerate and shale that have been metamorphosed slightly to moderately. However, because of their almost total lack of intergranular porosity, they resemble in hydrologic properties the crystalline rocks more closely than the clastic rocks. Because of their brittleness the quartzose rocks are highly fractured at many places, particularly in the vicinity of faults or contacts with older rocks.

In parts of the Piedmont Upland the quartzose rocks attain a thickness of more than 1,000 feet, and because of their hardness and resistance to weathering they form conspicuous ridges and hills. In the New England Upland, where these rocks generally are only a few tens of feet thick, they form inconspicuous low ridges or abrupt slopes at valley margins.

Basalt and Diabase of Triassic Age

In the Delaware River service area the youngest crystalline rocks are basalt and diabase--commonly called trap rock --of Triassic age. Both are dense dark rocks of igneous origin and consist mostly of approximately equal amounts of plagioclase and augite. The basalt is fine-grained and occurs as lava flows interbedded with the shale and sandstone of the Newark group; the diabase is coarser grained and forms sills intruded between the beds of sedimentary rock of the Newark group or as dikes cutting across those beds. Both the basalt and the diabase are much more resistant to erosion than the surrounding sedimentary rocks and form prominent ridges and hills several hundred feet high in the Triassic Lowland. The basalt forms a series of concentric arcuate ridges--the Watchung Mountains--in northern New Jersey, outside the Delaware River basin; the diabase forms many scattered hills and ridges across the basin and forms the well-known Palisades along the west bank of the Hudson River (pl. 12).

Hydrologic Properties of the Crystalline Rocks

In spite of their diverse origin, all the crystalline rocks have generally similar hydrologic properties: they have little or no intergranular porosity except in the weathered zone near the land surface; solution openings such as those in the carbonate rocks are scarce or absent; and practically all water in the fresh rock occurs in fracture openings. Porosity decreases with depth more rapidly than in any of the other rock types in the basin, and, except locally, little water is obtainable below a depth of about 300 feet.

As a general rule the following zones are encountered in downward succession in the crystalline rocks: (1) Soil and decomposed rock consisting of granular material--largely a mixture of clay, silt, and some sand; (2) disintegrated rock which downward contains more and more residual masses of fresher rock; (3) relatively fresh fractured rock; (4) fresh rock in which the fractures are closed by the weight of the overlying rock.

Usually these zones are gradational, and local exceptions to the sequence are common. At some places where erosion has been very active or the rocks are unusually resistant, fresh rock extends to the land surface, and in much of the glaciated part of the New England Upland, glacial deposits directly overlie fresh rock.

The thickness and character of the zones are related to numerous factors, among which are the landform, the type of rock, and the geologic history of the area. Other factors being equal, the weathered zone also varies considerably with rock type. The hardest and chemically most stable rocks, such as quartzite, tend to form the thinnest weathered zones, whereas the weak and chemically unstable rocks, such as much of the gneiss and schist of the Glenarm series, tend to form thick weathered zones. The thickness of weathered material in the outcrop of the Glenarm series of the Piedmont Upland commonly exceeds 25 feet and in places exceeds 50 feet.

The character of the weathered material is closely related to that of the parent rock; rocks high in quartz tend to form sand, whereas rocks such as gabbro which have little or no quartz form much less permeable clay and silt. Most of the crystalline rocks in the basin weather to an unsorted assemblage of clay, silt, and sand having moderate to low permeability.

Weathering is most active in the zone above the lowest level of the water table. The principal weathering agents in this area consist of dissolved carbon dioxide and oxygen and organic acids. Although some geologists believe that the lowest level of the water table is the lower limit of normal weathering processes (Penck, 1953, p. 61), much evidence exists to the contrary; in most crystalline-rock

areas in the Delaware River basin the zone of fluctuation of the modern water table is well above the base of the weathered zone. Ruxton and Berry (1957, p. 1275) list 3 reasons for such a seemingly anomalous condition: (1) Deep weathering may have taken place before an integrated circulation of water was established in the rock; (2) local deepening of the weathered profile may occur along prominent fractured zones; and (3) the level of the water table may be higher now than at the time the lower part of the weathered zone was established. In any case, considerable quantities of water now are stored in the weathered crystalline rocks in many parts of the Piedmont Upland and New England Upland, and water released from ground-water storage sustains the high base flow of the streams in those areas.

Fractures are caused by stresses of various origins. Deformation of the rocks during folding and faulting probably caused most fractures in the crystalline rocks of the basin, but shrinkage resulting from cooling of igneous rocks caused many fractures, particularly in the basalt and diabase. Depths to which open fractures extend are related to the strength and brittleness of the rock type as well as to the degree of deformation it has undergone. As a rule open fractures extend to greater depths in the hard quartzitic rocks than in the softer, less brittle rocks, such as phyllite and highly micaceous schist. Records of drilled wells indicate that open fractures do not ordinarily extend beyond a depth of about 300 feet, and that yields of wells are not increased appreciably by drilling below that depth. However, a few wells have obtained water from greater depths, probably from fractures along faults or in shattered pegmatite dikes and quartz veins.

The porosity of the fractured fresh crystalline rock is considerably less than that of the weathered zone, but the larger size of many of the fracture openings permits more rapid movement of water through them. The occurrence of water in fractured rock is much more irregular than in the highly weathered rock, owing to the unequal distribution of fractures. Adjacent wells commonly tap fracture systems that lack nearby hydraulic connection, so that pumping of one well may not affect the water level in the other, at least immediately. In the granular material in the weathered zone the water table may be the usual subdued replica of the topography, but in a fracture system, especially one in which the fractures are far apart and not interconnected freely, a true water table commonly is absent, and water will stand at different levels in each fracture or set of fractures. At some localities water-bearing fractures may be separated from the water-bearing weathered zone by a zone of dry unfractured rock; at other places, ledges of hard, massive rock separate water-bearing zones in the weathered material (Ward, 1956). Much study remains to be done before the occurrence of water in the crystalline rocks in the Delaware River basin is well understood.

As indicated by the rather limited data available, the coefficient of storage of the crystalline rocks probably ranges from about 0.005 to about 0.02--in the low range of values for unconfined conditions (Greenman, 1955, p. 6). The higher values probably are representative of the unconsolidated granular material in the weathered zone, whereas the lower values are representative of the fractured fresh rock.

The transmissibility and average permeability of these rocks also are moderately low to very low, as indicated by the reported specific capacities of wells. In the Piedmont Upland of northern Delaware, Rasmussen and others (1957, p. 99) reported the following specific capacities of wells tapping several types of crystalline rocks:

Table 7.--Specific capacities of wells in crystalline rocks of northern Delaware

Type of rock	Specific capacity in gpm per foot of drawdown			Number of wells
	Maximum	Minimum	Average	
Granodiorite (igneous)				
Weathered material	3.2	0.005	--	2
Hard rock	1.0	.07	0.3	10
Gabbro (igneous)	15	.003	1.6	33
Wissahickon formation	13	.01	.7	74

From these hydraulic characteristics it is apparent that a typical well tapping the crystalline rocks will exhibit considerable drawdown at any pumping rate, but substantial lowering of the water table will not extend far from the well, probably no more than a few hundred feet ordinarily, unless the rate of pumping is high.

Reported yields of 202 wells tapping crystalline rocks in the basin range from less than 1 gpm to more than 300 gpm and average about 50 gpm. Except for the basalt and diabase, which are perhaps the poorest water-producers in the basin and seldom yield more than a few gallons per minute to wells, differences in productivity among the many types of crystalline rocks seem to be outweighed by local differences within each type. Detailed studies should be made to determine the factors that affect the productivity of the crystalline rocks.

CARBONATE ROCKS

The carbonate rocks, as herein defined, consist of: (1) Limestone (calcium carbonate); (2) dolomite (calcium-magnesium carbonate; (3) rocks intermediate in composition between limestone and dolomite, sometimes called magnesian limestones; and (4) rocks intermediate between limestone or dolomite and other types, in which the carbonate

content is substantial. Included also is marble, a crystalline carbonate rock which resembles the noncrystalline carbonate rocks in its water-bearing properties.

The carbonate rocks comprise all or parts of several geologic or hydrologic units shown on plates 11 and 12 and listed in tables 1 and 6. In order of decreasing age these units include: Franklin limestone (Precambrian), Cockeysville marble of the Glenarm series of early Paleozoic (?) age, carbonate rocks of Cambrian and Ordovician age, and carbonate rocks of Silurian and Devonian age. These units are described briefly in the following pages.

Franklin Limestone

The Franklin limestone, one of the oldest rocks in the region (table 1), typically is a white or gray corase-grained to locally fine-grained marble or dolomitic marble which in places contains considerable amounts of graphite and many other minerals. The Franklin limestone is most abundant just east of the Delaware River basin in the New Jersey Highland of the New England province, but it occurs also at scattered localities throughout the New England province in the basin and in small areas in the Piedmont (pls. 11 and 12). The marble is associated with various types of gneiss and related crystalline rocks of Precambrian age.

Cockeysville Marble

The Cockeysville marble is a massive medium- to coarse-grained sugary marble which in places grades into impure schistose marble and limy mica schist. It underlies several small valleys in the southwestern part of the Piedmont Upland where it characteristically is covered by a thick residual deposit of clay.

The Cockeysville marble overlies the Setters formation and is overlain by the Wissahickon formation. All three formations are part of the Glenarm series.

Carbonate Rocks of Cambrian and Ordovician Age

The thickest and most extensive unit composed of carbonate rocks comprises several formations of Cambrian and Ordovician age which are grouped herein because of their general hydrologic similarity and because of the uncertainty of their correlation from one area to another. The formations are listed in tables 1 and 6 and are described briefly in table 1.

The Cambrian and Ordovician carbonate rocks crop out chiefly in the southern, lowland, belt of the Great Valley, but they occur also in Chester Valley in the Piedmont Upland, in small areas in the Triassic Lowland, and in several long, narrow valleys in the New England Upland (pls. 3, 11, and 12).

Typically, the Cambrian and Ordovician carbonate rocks consist of a thick sequence of limestone, shale, and slate, and, in the southern part of the Piedmont, some mica schist and phyllite. The limestone and dolomite weather to a thick residual deposit of clay and silt and form lowlands having only a few outcrops, whereas the zones containing noncarbonate rock types form low ridges and hills.

The total thickness of the carbonate rocks of Cambrian and Ordovician age ranges widely throughout the basin, but it is difficult to ascertain precise thicknesses, owing to the intense folding and faulting of the beds. The total stratigraphic thickness of the unit at any one locality may not exceed 2,500 feet, but because of folding and faulting the beds may extend to depths of 6,000 feet or more.

Carbonate Rocks of Silurian and Devonian Age

The carbonate rocks of Silurian and Devonian age comprise several relatively thin formations which are described briefly in table 1. In ascending order they are the Bossardsville, Decker, Rondout, Manlius, Coeymans, New Scotland, Becraft, and Port Ewen limestones. These formations crop out in a narrow belt across the Valley and Ridge province a few miles north of the Blue Mountain ridge. The beds dip steeply to the north and are within reach of wells in only a small area in and near the outcrop.

For the most part, the sequence consists of light-gray to nearly black limestone and dolomitic limestone, and smaller amounts of limy sandstone and shale. The total thickness of the beds probably does not exceed 800 feet within the basin, and in places the thickness is much less.

Hydrologic Properties of the Carbonate Rocks

The carbonate rocks differ from the other consolidated rocks in having a significant quantity of solutionally enlarged openings. Water percolating downward from the soil contains small amounts of dissolved carbon dioxide and organic acids which make a weak acid solution that is capable of dissolving carbonate rocks. Solution generally starts along pre-existing fractures or root cavities and enlarges them to form a network of more or less interconnected channels. Some such channels are enlarged to considerable size to form caverns, and in time a limestone may become honeycombed with caverns

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and the land surface pitted with sink holes; part of the drainage is on the land surface and the rest takes place through these underground solution channels.

The distribution of solution openings in most carbonate rocks is extremely irregular and is difficult to predict in advance of drilling. In some of these rocks, particularly those that are sandy or shaly and contain less calcium carbonate, solution openings may be virtually absent, and all the water may occur in ordinary fracture openings similar to those in unweathered crystalline rocks. Where the fractures are tightly closed, as in some of the Jacksonburg limestone of Middle Ordovician age, little or no water may be yielded to wells. In the Delaware River basin the most abundant fracture and solution openings are between depths of about 50 to 300 feet, although some wells have encountered large openings at depths of more than 1,000 feet. Openings also seem to be more abundant in the vicinity of surface streams.

Overlying the fresh carbonate rocks at most places is a weathered zone commonly as much as 50 feet thick, composed of residual clay, silt, and some sand. Owing to its considerable clay content, this material generally has rather low permeability and specific yield, and it does not ordinarily yield much water to wells. However, at some localities, such as in the outcrop of the Cockeysville marble in the Piedmont where the weathered zone averages more than 80 feet in thickness, the few available data suggest that the yields from the weathered material may exceed those from the underlying fresh rock where the fresh rock contains relatively few solution openings (Rasmussen and others, 1957, p. 102).

Ground water in the carbonate rocks occurs under unconfined to rather completely confined conditions. Unconfined or semiconfined conditions prevail in the weathered zone and in the immediately underlying fractured rock. The deeper fractures and solution channels contain semiconfined to confined water and may, in some places, transmit water many miles from intake areas to discharge areas.

Solution channels usually are more abundant near streams, and at many places surface drainage is controlled by the distribution of the subsurface openings. Stream valleys and other relatively low areas are therefore favorable sites for wells.

Streamflow in areas underlain by carbonate rocks is unusually steady and includes a high proportion of base flow--chiefly ground-water discharge. Water budgets are particularly difficult to estimate for drainage basins in carbonate-rock terrane, because much of the water that moves through the networks of solution channels may enter drainage basins underground from adjacent basins or may leave the basins as unmeasured ground-water outflow.

Detailed data on hydraulic coefficients of carbonate-rock aquifers of this region are lacking. However, from observed behavior of pumped wells tapping the artesian zone, and the effects of the pumping on adjacent wells, it may be concluded that a decline of artesian pressure as an effect of pumping generally is transmitted rapidly to some distant points but seldom is transmitted equally in all directions. In fact, nearby wells may tap different systems of rock openings, in which case the pumping of one well will not appreciably affect the water level in the adjacent well, at least immediately.

The transmissibility and average permeability of many carbonate-rock aquifers appears to be high, as indicated by reported yields of several hundred gallons per minute with pumping drawdowns of less than 20 feet. Small yields with large drawdowns are not uncommon, however, which suggests great variability in the aquifers. In the fresh rock, coefficients of storage probably are in the order of 0.0001 to 0.001 (Barksdale, Greenman, Lang, and others, 1958); in the weathered zone near the land surface, where water-table conditions prevail, the storage coefficients may be in the order of 0.01 to 0.10.

Although successful wells in the carbonate rocks yield larger supplies than wells in any other type of consolidated-rock aquifers, unsuccessful wells or wells having disappointingly low yields are not uncommon. In some areas, particularly where noncarbonate rock types are abundant among the carbonate rocks, yields of wells average less than 25 gpm, and the drilling of two or more test wells may be required to obtain a successful supply well. At other localities, especially in the stream valleys, although test wells may still be needed, well yields exceeding 500 gpm have been obtained, and yields of as much as 1,500 gpm are reported.

In the Pennsylvania part of the Delaware River basin, reported yields of 127 wells in carbonate rocks range from 4 to about 1,500 gpm and average nearly 200 gpm. Modern drilled wells 300-500 feet deep in the relatively pure carbonate rocks may be expected to yield about 50-500 gpm, but wells in formations, such as the Jacksonburg limestone, that contain considerable amounts of noncarbonate rocks are generally incapable of producing more than domestic or small-scale farm supplies.

CLASTIC ROCKS

Consolidated clastic rocks consist chiefly of fragments of rocks or minerals which have been derived from the disintegration of older rocks, transported to the site of deposition, and cemented or otherwise consolidated there. In the Delaware River basin area these rocks represent both marine and nonmarine depositional environments. but with a few local exceptions all the rocks

now contain fresh water at depths ordinarily penetrated by wells. The clastic rocks are the most extensive aquifers in the Appalachian Highlands; they underlie most of the Valley and Ridge province and the Triassic Lowland, and all the Appalachian Plateaus.

All the principal types of clastic rocks, ranging in texture from fine-grained shale in which the grains are microscopic in size to conglomerate containing boulders as much as several feet in diameter, are represented in the basin. On the basis of both their age, as determined from fossil content and less direct lines of evidence, and their physical character, or lithology, the clastic rocks have been subdivided into numerous geologic formations. These are described briefly in table 1 and listed also in table 6. The general characteristics of these rocks in each of the three major areas where they occur are discussed in the following pages. More detailed descriptions of the individual formations are given by Hall (1934) and Lohman (1937).

Rocks of the Valley and Ridge Province

Except for parts of the Great Valley and a narrow belt several miles north of Blue Mountain which are underlain by carbonate rocks, all the Valley and Ridge province is underlain by clastic rocks.

The oldest clastic formation exposed in the Valley and Ridge province is the Martinsburg shale of Ordovician age. Lying on the eroded surface of the Martinsburg shale is the Shawangunk conglomerate of Silurian age, which dips moderately to steeply northward and forms the Blue Mountain ridge.

From the Shawangunk conglomerate upward, the formations of Silurian to Pennsylvanian age are folded into a series of anticlines and synclines and are cut by numerous faults. A large volume of the originally deposited material has been removed by erosion since the end of the Paleozoic era (table 1), so that only the "roots" of the anticlines and synclines remain. The harder beds of sandstone and conglomerate form ridges rising to altitudes of as much as 2,000 feet above sea level; the softer beds of shale and some limestone form the intervening valleys.

The clastic rocks of the Valley and Ridge province include conglomerate, sandstone, siltstone, claystone, shale, and slate which occur in alternating bed or zones of variable thickness and extent. Most of the thicker beds or sequences of beds can be

identified over large areas and form mappable units, or geologic formations. Some formations have a distinctive character and are composed predominantly of one rock type. However, most of the thicker formations are more or less heterogeneous and contain numerous alternating layers of different rock types, each having distinctive hydrologic properties. The formations are described briefly in table 1.

Martinsburg Shale

The most extensive formation in the Valley and Ridge province is the Martinsburg shale, which underlies the northern part of the Great Valley in a belt 6 - 13 miles wide extending east-northeasterly across the basin. It occurs also farther south in several long, narrow belts bounded by the carbonate rocks of Cambrian and Ordovician age. The Martinsburg consists largely of gray shale which in many places is metamorphosed slightly to form slate, but it also includes sandstone, particularly in the upper part, and some conglomerate.

In an extensive area between the Delaware and Schuylkill Rivers thick zones of slate of commercial quality are mined for roofing material and other uses. In the slate the bedding of the original shale has been obscured by metamorphism, and instead, a prominent cleavage, usually at a considerable angle to the bedding, is developed.

The most widely accepted value for the maximum thickness of the Martinsburg shale in the basin is about 4,000 feet; however, Behre (1933), using a different interpretation of the geologic structure, estimated a maximum thickness of nearly 12,000 feet.

Although the shale and slate have little or no effective intergranular porosity, small but dependable supplies of water are yielded from fractures in these fine-grained rocks. The sandstone beds in the weathered zone contain some water in the intergranular pores where the cementing material has been leached out, and these beds generally are more permeable than the shale and slate. Most water yielded to wells in the Martinsburg shale is from depths of less than 200 feet, and it is seldom profitable to prospect beyond that depth. Most drilled wells yield less than 50 gpm, but a few yield 50-250 gpm.

The outcrop of the Martinsburg shale is a dissected upland in which the bottoms of the narrow, steep-sided stream valleys lie as much as 500 feet below the broad interstream areas. The soils commonly are less than a foot thick and have relatively low infiltration capacity and storage capacity, in the underlying rock is small; hence,

a relatively large proportion of the precipitation runs off as overland flow. In the glaciated area to the northeast, however, a mantle of glacial deposits acts as a more permeable intake, and streamflow probably is less flashy there.

Conglomerate and Sandstone Aquifers

The beds of conglomerate and coarse-grained sandstone are more resistant to erosion than the adjacent shale and thin-bedded sandstone, therefore they form prominent rocky ridges. The thickest and coarsest beds are those in the Shawangunk conglomerate, the Oriskany sandstone, the Pocono formation, and the Pottsville formation (table 1). Although these formations are not tapped by many wells, they very likely are the most permeable bedrock aquifers in the Valley and Ridge province.

Water occurs both in the fairly abundant fractures in the brittle quartzitic sandstone and conglomerate, and in the intergranular voids in the rocks of the weathered zone where the cementing material has been dissolved. Less permeable beds of sandstone or shale locally confine water, and flowing wells have been developed at several localities.

Data on hydraulic coefficients of the conglomerate and sandstone aquifers are not available; however, the physical characteristics of these rocks and the behavior of wells tapping them indicate that modern drilled wells more than 100 feet deep might be expected to yield about 50-300 gpm. Lohman (1937) reported that in Schuylkill County, Pa., several public-supply wells ranging in depth from 350 to 1,000 feet in the Pottsville formation yielded 65 to more than 125 gpm. However, he reported also that several deep wells had been unsuccessful in that area, owing to the absence of fractures in the rock penetrated.

Because of their firmly cemented character and very high content of quartz, the fresh conglomerate and sandstone are difficult and costly to drill. Moreover, the yields of wells in these rocks do not always increase with depth. There is always a risk involved in drilling for water in these rocks, and the deeper the drilling proceeds the less chance of getting large supplies becomes.

Interbedded Sandstone and Shale Aquifers

Several formations in the Valley and Ridge province consist not predominantly of one rock type, but, instead, of alternating layers of coarse- to fine-grained sandstone, shale, siltstone, claystone, and some conglomerate. In order of decreasing age these formations include: (1) the Bloomsburg red beds--a sequence of

red and green shale, sandstone, and some conglomerate which is largely of nonmarine origin; (2) the Mahantango formation of Willard (1935)--mostly beds of gray flaggy sandstone and shale of marine origin; (3) the Portage group, as used in Pennsylvania,--several formations consisting of thin-bedded to thick-bedded sandstone and sandy shale of marine origin which form broad ridges having moderate relief; (4) the Catskill formation--a thick sequence of red, brown, gray, and green somewhat lenticular beds of sandstone, shale, and conglomerate of nonmarine origin which also underlies nearly all the Appalachian Plateaus province; (5) the Mauch Chunk formation consisting of red and green shale and sandstone with some conglomerate in the upper part; (6) the Allegheny formation--the coal-bearing sequence containing irregular beds that range from shale and fire clay to coarse-grained sandstone and conglomerate.

It is difficult to generalize about the hydrologic properties of such a heterogeneous class of rocks. However, the beds of sandstone generally seem to be somewhat more permeable than the beds of shale. In weathered sandstone some water occurs in intergranular pores as well as in fractures, but water in the shale is contained almost entirely in fractures, many of which are along the bedding planes. Artesian conditions, which are common, are caused by the dipping beds of quite different permeability. Water-table conditions generally occur in the weathered rock near the land surface.

Reported yields of wells in the interbedded sandstone and conglomerate aquifers have a great range. Some beds of shale yield only a few gallons per minute to wells, whereas wells tapping some beds of coarse-grained sandstone yield more than 150 gpm, and several deep wells are reported to yield more than 300 gpm.

Because it underlies valleys that contain important centers of population, the Mauch Chunk formation is a particularly important source of water supplies, even though much of the formation is composed of shale. It receives ample recharge from adjacent ridges, owing to its low topographic position. Reported yields of 100 wells in the Mauch Chunk range from less than 1 to 375 gpm and average about 50 gpm. However, the average yield, which is affected by the values for many small domestic wells, is too low to be presentative of yields that might be expected from deep drilled wells used for municipal and industrial supply.

In Schuylkill and Carbon Counties, Pa., where the Mauch Chunk formation is the most important source of ground-water supply, Lohman (1937) reported that many municipal and industrial wells yielded more than 100 gpm, and that a well in Schuylkill County, 452 feet deep, yielded 350 gpm with a drawdown of 217 feet--a specific capacity of 1.6 gpm per foot of drawdown. Assuming that the drawdown caused by entrance losses in the well was small and that the aquifer is artesian,

the coefficient of transmissibility probably is in the order of 3,000-4,000 gpd per foot.

Because of its location in the coal basins, the Allegheny formation offers a special case. Coal-mining operations have extensively dewatered parts of the formation, and in many places the mining operations have resulted in the formation of acid waters high in sulfate content, thus making the water at or near the mines unsuitable for most uses. Usable supplies of ground water may be obtained in the Allegheny formation in areas remote from mines, however.

Shale Aquifers

Three formations in the Valley and Ridge province, the Wills Creek shale, the Esopus shale, and the Marcellus shale, are composed of shale, siltstone, or claystone.

The Wills Creek shale, which generally is given the local name Poxono Island shale (of White, 1882), occurs in a narrow band just north of Blue Mountain where it is largely covered by glacial deposits and is not tapped by many wells. Little is known about its water-bearing characteristics.

The Marcellus shale and the Esopus shale, which are separated by the Onondaga limestone, are largely dark sandy shale or siltstone (pl. 2) and both contain hard slaty beds. These rocks are relatively impermeable, and the small amount of water they contain occurs almost entirely in fractures. In many localities the fractures are so tightly closed or so scarce that little or no water is yielded to wells. However, some wells in the more highly fractured rock yield as much as 25 gpm.

Rocks of the Appalachian Plateaus Province

The Appalachian Plateaus province, which occupies a third of the total area of the Delaware River basin, is underlain almost entirely by a sequence of sandstone, shale, and some conglomerate predominantly of nonmarine origin. This sequence, which in places is more than 6,000 feet thick, has been called the Catskill formation. The Catskill formation has been divided into several smaller units which are listed in table 6. Toward the west and southwest the nonmarine beds intertongue with marine formations of the Portage group (as used in Pennsylvania) and the upper part of the Hamilton group. The younger Pocono formation crops out on the west and southwest flanks of the plateaus and when detailed mapping is completed may be found to cover a larger part of the plateaus themselves than the area shown on plate 12. However, the question as to the presence or absence of the Pocono formation on the plateau is of little or no hydrologic importance because of the similarity of the Pocono to the immediately underlying part of the Catskill formation.

In contrast to the folded beds in the Valley and Ridge province, the beds underlying most of the Appalachian Plateaus province are either nearly flat lying or very gently folded. They consist largely of red, brown, gray, and green sandstone, shale and some conglomerate. Beds of homogeneous material range in thickness from a fraction of an inch to several tens of feet. The following log of a test boring typifies the character of the beds:

Well Svl14, New York City Board of Water Supply, test boring for shaft on line of East Delaware Tunnel, near Neversink River, about 4 miles southeast of Willowemoc, Sullivan County. Altitude of land surface 1,612 feet. (Compiled from driller's log).

	Thickness (feet)	Depth (feet)
Till	13	13
Shale, red	5	18
Sandstone, red	2	20
Sandstone, gray	25	45
Conglomerate, gray, white quartz pebbles	5	50
Sandstone, gray	15	65
Shale, gray	1	66
Sandstone, gray	4	70
Shale, red and gray	2	72
Sandstone, gray	62	134
Shale, red and gray	3	137
Sandstone, gray	27	164
Shale, sandy, gray	8	172
Sandstone, gray	9	181
Shale, gray	2	183
Sandstone, gray	13	196
Shale, red	22	218
Sandstone, gray, trace of coal at 237'	29	247
Shale, red, gray, some sandy shale	61	308
Sandstone, gray, and red, shale streaks	23	331
Shale, sandy, red	12	343
Sandstone, gray	20	363
Conglomerate, gray, some sandstone and shale	61	424
Sandstone, gray, some shale, in thin strata	162	586
Shale, sandy, red	7	593
Sandstone, gray, some shale	73	666
Shale, sandy, red	29	695
Sandstone, gray, vein of calcite, 0.4 foot thick, at 731 feet	43	738
Shale, sandy, red and green	5	743

Most of the beds are cut by comparatively smooth, regular planes of fracture (joints) which commonly consist of three mutually perpendicular sets, one of which is parallel to the bedding. Joints at oblique angles to the bedding are not uncommon, however. These joints greatly facilitated "quarrying" of the rock by the glacial ice that scoured most of the area several times during the Pleistocene epoch. Tablelike surfaces, bounded by nearly vertical cliffs as much as several tens of feet in height, have resulted from such quarrying action at many places.

Most of the consolidated rocks in the plateaus are covered by glacial deposits of varying thickness. These consist largely of till but include scattered bodies of outwash, some of which are of considerable size (pl. 14). Where permeable, these deposits, especially the outwash, absorb much of the precipitation and transmit some of it to the underlying bedrock; however, a large part of the till is relatively impermeable and does not allow much recharge to the underlying hard-rock aquifers. The exposures of bedrock, which probably cover less than 10 percent of the area of the plateaus, are characterized by numerous outcrops of rock and generally thin stony soils; these conditions result in rather low infiltration capacity.

The beds in the Catskill formation underlying the plateaus are moderately good to poor aquifers. Large variations in yield of wells occur within short distances, both vertically and horizontally. For example, dry holes as much as 400 feet deep have been reported in areas where successful wells are typical. Also, much deeper wells have been abandoned owing to great depths to water, to insufficient yields, or to poor chemical quality of water. In general, the beds of sandstone are more permeable than the beds of shale; however, some of the sandstone is so completely cemented and lacking in fractures that it yields little or no water.

Exceptional yields are obtainable in scattered large fracture systems, generally along faults or unusually large joints. Fluhr (1953) reported that flows of as much as 600 gpm were encountered in such zones at depths of as much as 1,700 feet below the land surface during the construction of water-supply tunnels. The tunnels were almost completely dry elsewhere, however.

Records of 371 wells in the Appalachian Plateaus in the Delaware River basin show ranges in depth from 5 to 960 feet, most wells being 100-300 feet deep. Reported water levels range from 11 feet above the land surface--flowing artesian wells are not uncommon--to 540 feet below. Yields of wells range from 0 to 600 gpm and average more than 25 gpm; specific capacities range from less than 0.2 to about 4 gpm per foot of drawdown. Springs are numerous and are used as sources of supply at many places.

Rocks of the Triassic Lowland

The Triassic Lowland, a broad belt 9-32 miles wide extending across the southern part of the Appalachian Highlands, is underlain chiefly by clastic rocks that belong to the Newark group of Triassic age (table 1). The clastic rocks are intruded by sills and dikes of diabase, and east of the basin in New Jersey they contain also several flows of basalt. The basalt and diabase are discussed in the section on crystalline rocks.

Most of the sedimentary rocks are of nonmarine origin and are believed to have been deposited under semiarid conditions in a northeast-trending basin having a somewhat greater extent than the present Triassic Lowland (Johnson and McLaughlin, 1957, p. 36). The rocks are a thick sequence of shale, sandstone, argillite, and conglomerate which lies on the eroded surface of the much older rocks of Precambrian and Paleozoic age (pl. 13) from which the materials were in large part derived.

The beds are tilted to the northwest in most of the region, although locally they dip in other directions where they are warped into broad folds, particularly in the vicinity of the masses of diabase. At most places the dips are less than 20 degrees, although adjacent to some of the large faults along the northwest border of the Lowland, dips are as much as 50 degrees. The maximum thickness of the Newark group in the Delaware River basin is about 12,000 feet along the Delaware River (Johnson and McLaughlin, 1957, p. 32).

The Newark group has been divided into three formations, each having more or less distinctive types of rock (Kümmel, 1897). From oldest to youngest, they are the Stockton formation, which is characterized by prominent beds of light sandstone high in feldspar content (arkose); the Lockatong formation, which is chiefly argillite and hard shale; and the Brunswick formation, which is a thick, monotonous sequence of red shale and sandstone. A fourth unit, commonly grouped with the Brunswick formation, consists of lenticular beds of conglomerate and coarse-grained sandstone. Unlike most of the formations of the Delaware River basin these formations are not clearly defined time units but instead are units representing changing conditions of deposition both in place and in time. In general, however, the Stockton formation is the oldest unit and the Brunswick is the youngest. The Lockatong formation represents a swamp and lake deposit near the center of the ancient Triassic basin, and intertongues with the lower part of the Brunswick formation in a wide area, largely in Bucks County, Pa. The extent of the formations is shown on plates 11 and 12 and their relations in cross section are shown on plate 13. Their physical and hydrologic properties are described briefly in table 1 and in somewhat more detail in the following sections.

Stockton Formation

The Stockton formation crops out in two principal belts, one in the southern and one in the central part of the Triassic Lowland, and also in two smaller areas--one mostly outside the Delaware River basin and between the two principal belts, the other along the Hudson River at the eastern margin of the Triassic Lowland, in northeastern New Jersey (pls. 11 and 12). The Stockton overlies the eroded edges of rocks of Precambrian to Ordovician age and is in turn overlain by the Lockatong formation or by the Brunswick formation where the Lockatong is absent. The thickness of the Stockton ranges from about 1,000 to 3,000 feet in the southern belt and reaches a maximum of about 5,000 feet in the central belt.

The most distinctive rock in the Stockton formation is a light gray or light yellow medium- to coarse-grained sandstone (an arkose) that contains much feldspar and some mica. Other types include conglomerate, fine-grained red or brown sandstone, and soft red shale. Sandstone and conglomerate generally are more abundant in the lower part of the formation than in the upper part. Individual beds are not extensive, although some of the thicker zones or sequences of beds extend for many miles. The rock materials appear to have been derived in large part from the crystalline rocks to the south and apparently were deposited in a nonmarine environment.

The beds of arkose and conglomerate form low ridges; the softer beds of red shale and sandstone form the intervening valleys. The soils formed on these rocks are nearly as variable as the rocks themselves; in general the soils are thickest and most permeable on the coarse-grained arkose and conglomerate and thinnest on the red shale where in places they are only a few inches thick.

The Stockton formation is one of the most productive of the consolidated aquifers in the Delaware River basin and adjacent New Jersey and has perhaps the highest average permeability of any of the clastic-rock formations. Most of the water in the Stockton occurs under confined or semiconfined conditions in the weathered and fractured rock within about 500 feet of the land surface. The most permeable beds are composed of coarse-grained arkose and conglomerate which contain water in fractures and also in openings between grains where the cementing material has been removed by weathering. Most of the intervening beds of shale are much less permeable and act as aquicludes confining water in the arkose and conglomerate aquifers.

Recharge to the aquifers in the Stockton formation percolates downward in their outcrop areas, joins the ground-water body, and moves in the direction of the hydraulic gradient to points of discharge.

Preliminary pumping tests have given coefficients of storage of about 0.00001 or 0.00002, indicative of artesian conditions; probably nowhere does the coefficient exceed about 0.001 (Greenman, 1955, p. 28). Laboratory-determined specific yields of a dozen samples of arkose, conglomerate, sandstone, and sandy siltstone from outcrops of the Stockton formation (U. S. Geological Survey Water Resources Laboratory, Denver, unpublished data) ranged from nearly 0 to 19 percent and averaged about 8 percent. Porosities in these samples ranged from 7 to 30 percent and averaged about 15 percent.

Coefficients of permeability for movement of water parallel to the bedding determined in 10 of the 12 laboratory samples ranged from 0.001 to 0.3 gpd per square foot and averaged only 0.04 gpd. Permeability coefficients for movement perpendicular to the bedding ranged from 0.001 to 0.2 and averaged about 0.03 gpd per square foot--somewhat less than the average permeability for movement parallel to the bedding. Both these average values are much less than the average permeability of arkose and conglomerate aquifers suggested by well-yield data, which indicates that the most of the water probably moves toward pumped wells through the fractures in the rock rather than through the intergranular pores. However, the surprisingly high specific yields for the laboratory samples of weathered rocks suggest that most of the ground-water storage capacity in the aquifers of the Stockton formation is in the pore spaces between grains in the weathered zone near the land surface rather than in the fractures, even though the water moves much more readily through the fractures. As a result, wells may have relatively high initial yields, owing to the high permeability of the fractured zones, but the ultimate or long-term yields may be substantially less, because they are governed by the much lower permeability of the weathered granular materials that supply most of the water withdrawn from storage. A more favorable aspect is that the low permeability of the granular materials allows them to retain water in storage for considerable periods.

Reported yields of 180 wells tapping the Stockton formation in the Delaware River basin range from 2 to 800 gpm and average about 100 gpm. Specific-capacity tests for 23 wells in Bucks County, Pa., showed a range in values from 0.35 to 44 gpm per foot of drawdown and on an average of about 6.0 gpm per foot (Greenman, 1955, p. 28).

From all these data it may be concluded that most deep drilled wells of modern design in the Stockton formation should obtain yields in the range of 30 to 300 gpm, but that the long-term yields under continuous pumping would be substantially less than the initial yield. Because of the low coefficients of storage and the relatively high coefficients of permeability of the artesian aquifers, drawdown effects of pumping would extend considerable distances, so that proper spacing of wells to minimize interference is particularly important.

Runoff from the outcrop of the Stockton formation probably is less flashy than that from the other formations in the Triassic Lowland, owing to the greater permeability of many of the beds and the thicker soils.

Lockatong Formation

The Lockatong formation overlies the Stockton formation and crops out in three principal belts lying north or northwest of the outcrops of the Stockton in the central and south-central parts of the Triassic Lowland (pl. 11). The Lockatong is absent in most of the Lowland northeast of the Delaware River basin and is missing also in the western part of the basin. It attains a maximum thickness of more than 3,800 feet in the outcrop along Tohickon Creek and the Delaware River (pls. 11 and 13).

The most abundant and distinctive rock type is a thick-bedded dark-gray to black argillite (hard claystone or siltstone). Other types include thin-bedded dark shale, impure limestone, and limy argillite. The upper part of the Lockatong, which grades into the Brunswick formation, includes tonguelike beds of dark-red argillite and red shale of the type occurring in the Brunswick formation. A thin zone at the base of the Lockatong contains coarse-grained beds like those in the underlying Stockton formation.

The argillite is a dense, hard rock and forms prominent ridges where it is interbedded with softer shale, or broad plateaus where the soft rocks are absent. Most of the formation weathers to thin soil composed of yellowish-brown clay loam.

The Lockatong formation contains some of the least permeable rocks in the basin. The fresh argillite has very little intergranular porosity, and fracture openings in this rock are neither large nor abundant. Most of the water occurs under unconfined or semiconfined conditions in the weathered zone near the land surface.

Yields reported for 205 wells in the basin and adjacent New Jersey range from 0.2 to 55 gpm and average about 10 gpm; specific capacities reported for 65 wells range from 0.02 to 2.0 gpm per foot of drawdown and average about 0.6 gpm per foot (Barksdale, Greenman, Lang, and others, 1958).

Runoff from the outcrop areas of the Lockatong formation probably is extremely flashy because of the low infiltration capacity of the thin impermeable soils and the small ground-water storage capacity available to sustain base flow.

Brunswick Formation

The Brunswick formation is the thickest and most extensive formation in the Triassic Lowland (pls. 11, 12, and 13). In the Delaware River basin its outcrop is about equal in area to the combined outcrops of the Stockton and Lockatong formations; in New Jersey outside the basin it underlies most of the Triassic Lowland. Its maximum thickness within the basin probably is about 7,000 feet; outside the basin in New Jersey, where the Brunswick includes beds that are probably equivalent to the Lockatong formation and possibly to part of the Stockton formation as well, the total thickness may be greater.

The Brunswick formation typically consists of soft red shale interbedded with smaller amounts of brownish-red siltstone and fine-grained sandstone, and green, yellow, gray, and purple shale and argillite. East of the basin, sandstone is more abundant, and beds of conglomerate occur in places. Along the northern border of the Triassic Lowland the fine-grained materials grade into conglomerate and coarse-grained sandstone (pls. 11 and 12) that probably represent alluvial-fan deposits laid down by torrential streams near the end of Triassic time (Johnson and McLaughlin, 1957). In the vicinity of the Delaware River and to the west in Bucks County, the lower part of the Brunswick is gradational with the upper part of the Lockatong formation and includes beds of dark argillite interbedded with the typical red shale. Near the intrusive masses of diabase, the soft red shale of the Brunswick formation is altered to a hard dark finely crystalline rock (hornfels) that closely resembles argillite (pl. 13).

Because of its great extent and its relatively high average permeability, the Brunswick formation is one of the most important sources of ground-water supplies in the Appalachian Highlands. The weathered part of the formation above a depth of about 250 feet contains unconfined water and may be regarded as a water-table aquifer. Between depths of about 250 and 600 feet semiconfined water occurs in relatively permeable zones which rarely are more than 20 feet thick.

The upper, water-table aquifer receives recharge directly from precipitation; the underlying semiartesian aquifers are in turn recharged by drainage from the water-table aquifer. In the semiartesian aquifers the water-bearing openings are fractures, many of which have been enlarged slightly by the solution of limy material by circulating ground water. In the water-table aquifer, fractures are more abundant, and additional drainable water may be stored in the intergranular pores in the coarser materials. Herpers and Barksdale (1951, p. 27) reported a specific yield of 1 to 2 percent for the zone within 300 feet of the land surface; a decline in water table of a foot over an area of a square mile therefore would represent a release from storage of approximately 2 to 4 million gallons.

Most wells in the Brunswick formation tap both water-table and semiartesian aquifers. The ultimate yield of a well is related to the storage capacity of the water-table aquifer it penetrates and the rate at which that aquifer can supply recharge to the underlying semiartesian aquifers tapped by the well. As in the Stockton formation the long-term yield of a heavily pumped well may be only a fraction of the initial yield.

Reported yields of 164 wells in the basin range from 2 to about 400 gpm and average about 90 gpm. East of the basin where the Brunswick formation contains a higher proportion of coarse-grained beds the average yield of wells is higher; at Ridgewood in Bergen County, N. J., well yields up to 750 gpm are reported.

Most of the soils on the Brunswick formation are thin and not very permeable, hence their infiltration capacity is rather low. Moreover, the ground-water storage available to accept recharge commonly is small. The runoff from the outcrop therefore probably is very flashy.

UNCONSOLIDATED SEDIMENTS OF GLACIAL ORIGIN

Continental glaciers covered all the northern part of the Delaware River basin at least three, and possibly four times during the last million years. The last ice sheet--that of the Wisconsin glacial stage (table 1)--retreated from the region about 10,000 years ago (Flint 1957). The Wisconsin ice sheet and its predecessors--those of the Illinoian and Kansan(?) stages (pl. 14)--removed the soil and loose weathered material, quarried and scraped the underlying fresh rock, modified the pre-existing drainage pattern, deepened some of the stream valleys and filled others with deposits, and left a mantle of unsorted deposits as till or ground moraine over most of the area. Ridges composed of unsorted debris were deposited at the margins of the ice as terminal and recessional moraines, and lateral moraines accumulated along the margins of some of the ice tongues in the valleys. Glacial outwash and other stratified deposits were laid down in the valleys and along the margins of the ice masses by meltwater streams, and fine-grained sediments were deposited in lakes and marshes. Southward-flowing meltwater streams deposited outwash in the major valley far south of the ice margin.

On the basis of their hydrologic properties the glacial sediments of the basin are herein divided into two main categories, unstratified glacial sediments and stratified glacial sediments, which are described briefly in the sections following.

Unstratified Sediments

The unstratified sediments, which were deposited directly by the ice, consist of unsorted materials ranging from clay to boulders and having relatively low permeability. The most extensive of these deposits is till, which blankets perhaps 90 percent of the glaciated area. Other unstratified sediments are the morainal deposits of various types, which differ from the till chiefly in their greater thickness and their distinctive landform expression as curved or sinuous ridges, and their somewhat greater content of permeable bodies of sand and gravel.

The oldest glacial deposits--those of Kansan[1/] (?) age--consist largely of scattered boulders south of the Illinoian border (pl. 14). Scattered thin deposits of Illinoian age occur south of the Wisconsin border, but only a few of the thicker masses, such as the terminal moraines near Allentown, Pa., are shown as early glacial drift on the geologic map (pl. 14). North of the Wisconsin border the till and moraines are almost entirely of the Wisconsin glacial age; the earlier deposits of Kansan (?) and Illinoian age were largely reworked by the Wisconsin ice and incorporated into the younger deposits.

The till consists of an unsorted mixture of particles ranging in size from clay to boulders many feet in diameter. The character of the materials varies from place to place, depending on the nature of the parent rocks. Sand and gravel are abundant where the materials are derived largely from sandstone but clay predominates where the parent rocks are mostly shale. Limestone is not an abundant constituent of till at most places in the Delaware River basin.

In the broad upland areas the till generally is less than 30 feet thick, but in buried valleys the thickness is greater; Fluhr (1953) reported a thickness of as much as 350 feet in Delaware County, N. Y. In many of the present stream valleys fairly thick masses of till are interbedded with glacial outwash (pl. 15).

The overall permeability of till is very low, owing to the usual moderate to large content of clay and silt, and the fact that smaller particles commonly fill spaces between larger ones. Direct runoff from most till-covered areas is large because of the low infiltration capacity of the materials. At many places till forms an aquiclude confining water in permeable outwash deposits, with which it is interbedded, or in the underlying bedrock. Much till in the upland area contains bodies of perched water lying above zones rich in clay or dense, relatively impermeable bedrock.

1/ Deposits of Kansan (?) age are sometimes referred to locally as Jerseyan drift.

Yields of most wells in till are only a few gallons per minute. Rates of inflow into the wells commonly are even less, so that dug wells having large storage capacity are used. Such wells can be pumped for short periods at considerably greater rates than they could be pumped continuously. Most dug wells extend only a short distance below the water-table and depend on frequent precipitation for recharge. Seasonal water-table fluctuations in till may be large (pl. 16), and many wells are reported to go dry after several weeks, others require months of drought.

The moraines are believed to be similar to the till in hydrologic characteristics, except that they are thicker than most of the upland till, and probably are more reliable as sources of perennial water supplies. The older morainal deposits south of the Wisconsin border, (pl. 14) such as those in the vicinity of Allentown, Pa., are generally more highly weathered and less permeable than the moraines of Wisconsin age.

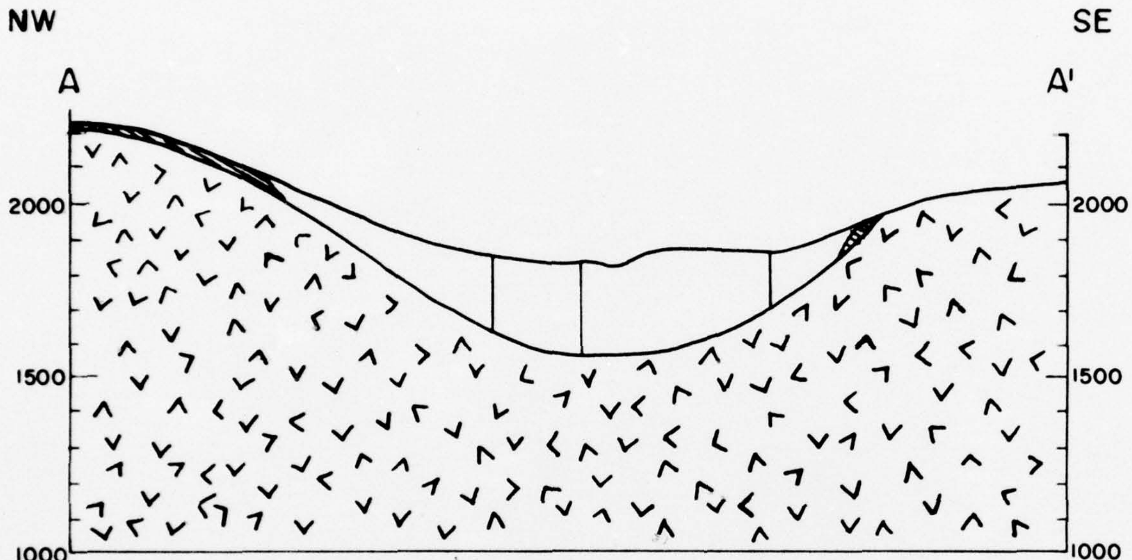
Stratified Sediments

In the Appalachian Highlands the stratified sediments were deposited: (1) in the open valley bottoms by meltwater streams as glacial outwash; (2) in depressions on the ice as kames; (3) in long, sinuous ridges beneath the ice as eskers; (4) along the valley sides at the margines of the ice tongues as kame terraces; and (5) in glacial lakes and marshes as deltaic, marsh, and lake-bottom deposits. Alluvium of postglacial (Recent) age occurs as thin stream and marsh deposits which are difficult to distinguish from the underlying deposits of Pleistocene age.

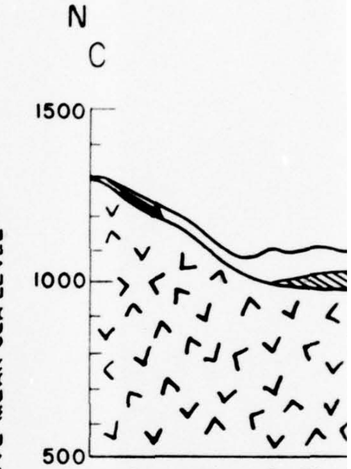
Although these deposits are as heterogeneous as the till and morainal deposits, they differ in having definite bedding as a result of being sorted by water. The most evenly bedded, and also the most fine-grained, sediments are the lenses and layers of clay, silt, and fine sand that were deposited in lakes and marshes dammed either by the ice or by moraines and rock walls beyond the ice margin. Such deposits are most widespread in the area of the ancient Lake Passaic in northern New Jersey, near the cities of Morristown and Madison (pl. 14) smaller masses of similar deposits occur at many other localities. Outwash is fairly well bedded, but the individual beds are exceedingly lenticular. The ice-contact deposits--those in kames, kame terraces, and eskers--commonly are chaotically or crudely bedded (pl. 2) and locally contain bodies of till derived from the adjacent ice.

The outwash, which is the most abundant and important of the stratified sediments, forms elongate masses partly filling the preglacial stream valleys. Tongues of outwash extend along the major

U. S. GEOLOGICAL SURVEY

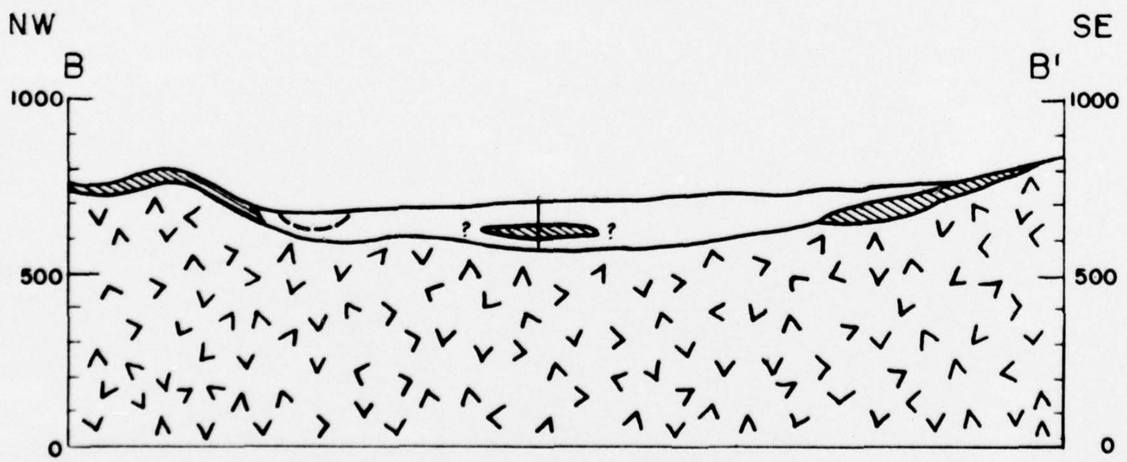


Geologic section A - A' across Willowemoc Creek,
Willowemoc, Sullivan County, N.Y.

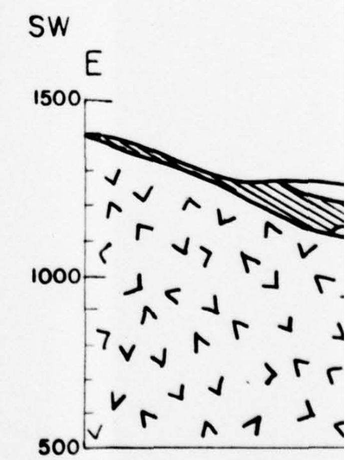


Geologic section C - C' ac
Delaware River, Downsville,

ALTITUDE, IN FEET, ABOVE MEAN SEA LEVEL

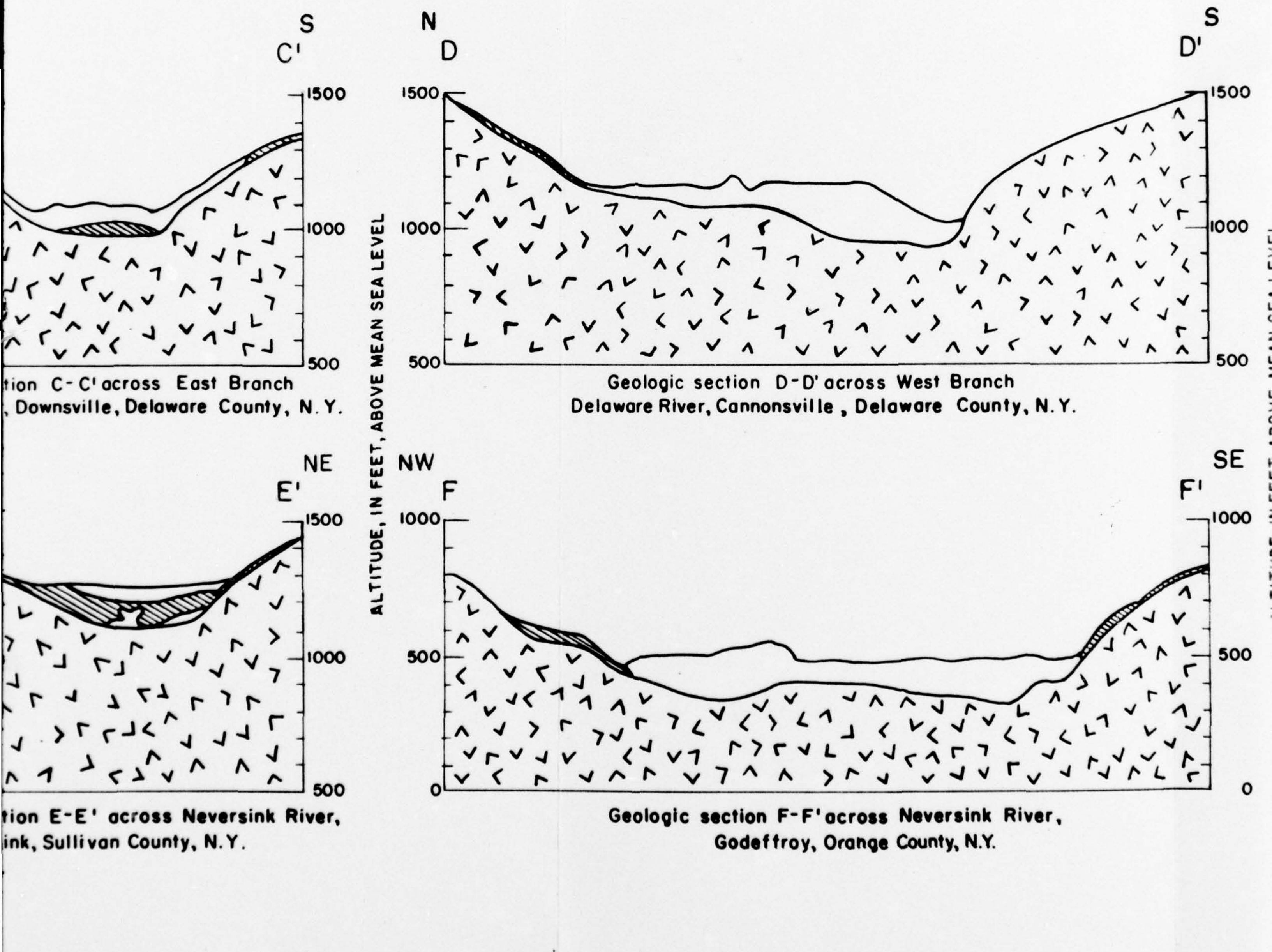


Geologic section B - B' across Delaware River,
Narrowsburg, Sullivan County, N.Y.



Geologic section E-E' a
Neversink, Sullivan

GEOLOGIC CROSS SECTIONS



tion C-C' across East Branch
, Downsville, Delaware County, N.Y.

Geologic section D-D' across West Branch
Delaware River, Cannonsville, Delaware County, N.Y.

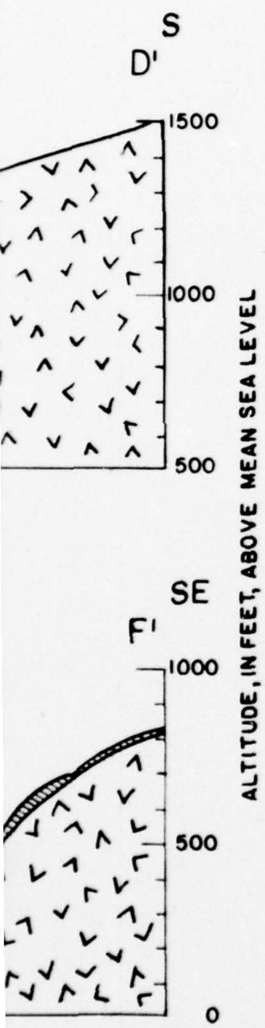
tion E-E' across Neversink River,
ink, Sullivan County, N.Y.

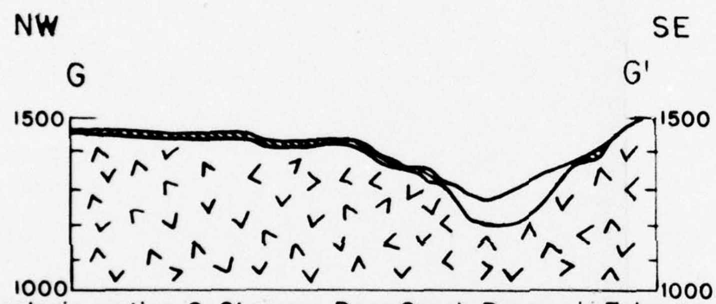
Geologic section F-F' across Neversink River,
Godeffroy, Orange County, N.Y.

TIONS OF MAJOR STREAM VALLEYS IN NORTHERN PART OF

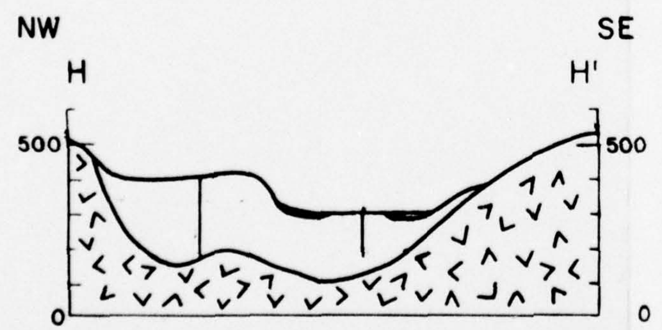
2

PLATE 15



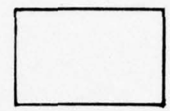


Geologic section G-G' across Bear Creek Reservoir Enbankment, Carbon and Luzerne Counties, Pa.

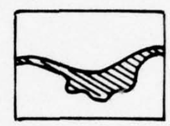


Geologic section H-H' across Tocks Island Dam Site, Monroe County, Pa., and Warren County, N.J.

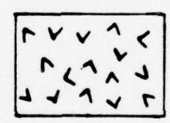
EXPLANATION



Outwash and alluvium
(Sand, gravel, and some silt)



Till and lake deposits
(Boulders, sand, silt, and clay)



Consolidated bedrock

Well or test boring

Horizontal scale

Note: Sections C-C', D-D', E-E', and F-F' modified after T. W. Fluhr, Senior Geologist, New York City Board of Water Supply, 1953. Sections G-G' and H-H' modified after data fro U.S. Corps of Engineers, 1957

Locations of cross-sections shown on plate 30

PART OF DELAWARE RIVER BASIN

3

valleys far beyond the borders of the glaciated areas into the Coastal Plain province. The Cape May formation in the Coastal Plain may be in part equivalent to the outwash of Wisconsin age, and the Pensauken and Bridgeton formations may be in part equivalent to the older outwash.

Cross sections of the outwash in the Appalachian Highlands (pl. 15) are typically U-shaped in basal outline as a result of quarrying and scour of the bedrock by the ice that occupied the valleys before the outwash was deposited. At many places the locations of the present streams do not coincide with the centers of the old valleys cut in the bedrock surface, and ridges of bedrock extend to the land surface at numerous places in the present valleys. The outwash generally ranges in thickness from about 50 to 200 feet, although locally it is thicker. Stratified deposits as much as 500 feet thick occur, however; such thick deposits generally form kame terraces along valley margins and only the lower part is saturated.

Water occurs in the stratified glacial sediments under unconfined to semiconfined or confined conditions. Under natural conditions the deposits are recharged largely by infiltration of precipitation on their outcrop; the outwash in the valleys also receives some recharge from adjacent and underlying bedrock and from till along the valley sides. Under conditions of development, where the normal hydraulic gradients toward streams and lakes are reversed by pumping, recharge may be induced from surface-water bodies and these may also include leakage from septic tanks, cesspools, and from sewers or other underground pipes. Most natural discharge of ground-water is into streams and lakes and into the atmosphere as evapotranspiration. Artificial discharge is chiefly through pumped wells; although leaky sewers below the water table may drain away some water in places, they may yield water in other places where the head in the sewer is above the water table.

Some of the coarser and thicker deposits of outwash constitute the most productive aquifers in the entire Delaware River basin area, although in some localities where silt and clay predominate, yields of wells are disappointingly low. Reported yields of 55 wells tapping outwash in the basin range from 2 to 900 gpm. The median yield of 28 large-diameter drilled wells used for industrial or public supply is 215 gpm. Sustained-yields of as much as several thousand gallons per minute doubtlesss could be obtained largely from induced recharge to deposits of coarse-grained sand and gravel that are hydraulically connected with perennial streams. The advantages and disadvantages of pumping from wells versus pumping or diverting the water directly from the stream would, of course, have to be appraised locally. As often as not the quality and temperature of the water would be as important as the quantity.

RECHARGE AND DISCHARGE

The aquifers of the Appalachian Highlands are recharged largely by infiltration of precipitation on their outcrops or on the overlying blanket of glacial sediments. Seepage from the headwater reaches of some streams probably contributes a small amount of additional recharge, and some of the aquifers in the valleys are recharged in part from the adjacent ridges.

The infiltration capacity of the outcrops is a function of several variable factors, among which are the permeability of the soil and underlying weathered rock and the topography. The infiltration capacity ranges from very high in the sandy and gravelly glacial outwash to low in the thin, poorly permeable soils on the shale of Triassic age and in the outcrops of dense, massive rocks.

The average rate of natural recharge to the aquifers of the Appalachian Highlands ranges more widely and is more difficult to estimate than the recharge to the aquifers of the Coastal Plain. However, the average recharge in the Highlands may be estimated very approximately by comparison with a nearby area of similar climatic, hydrologic, and geologic conditions where a detailed water budget was worked out--the basin of the Pomperaug River, Conn., reported by Meinzer and Stearns (1929).

The Pomperaug River basin, an area of 89 square miles in west-central Connecticut, is underlain largely by crystalline rocks except for the south-central part, which is underlain by diabase and sedimentary rocks of Triassic age; these consolidated rocks are covered by a discontinuous mantle of glacial deposits (Meinzer and Stearns, 1929, p. 76-77).

Water budgets for the Pomperaug River basin and the Appalachian Highlands part of the Delaware River basin are compared in table 8. The data from the Pomperaug River basin have been modified slightly to allow for change in storage during the budget period, 1913-16.

Table 8.--Water budgets for Pomperaug River basin, Conn., and Appalachian Highlands part of Delaware River basin

Item	Pomperaug River basin[1]			Appalachian Highlands in Delaware River basin	
	Mgd per sq mi	Percent of precipitation	Percent of runoff	Mgd per sq mi	Percent of precipitation
Precipitation	2.12	100	--	2.10	100
Water loss	1.13[2]	53[2]	--	1.04	49
Runoff	.98	47	100	1.07	51
Direct runoff	.55[2]	26[2]	56[2]	--	--
Base flow (ground-water runoff)	.43[2]	21[2]	44[2]	--	--
Ground-water recharge	.74	35	--	--	--

1/ Data modified from Meinzer and Stearns (1929)

2/ Figures adjusted to allow for change in storage during budget period.

The similarity of the values of precipitation, water loss, and runoff in the two areas is at once apparent. Streamflow data for the Delaware River basin are not sufficiently detailed to permit estimates of direct and base, or ground-water, runoff. However, the value of 44 percent for the base-flow portion of total runoff determined in the Pomperaug River basin study is believed to be somewhat lower than the average value in the Appalachian Highlands of the Delaware River basin. The Pomperaug basin is entirely glaciated and has relatively thin soils of low permeability, whereas only the northern part of the Highlands in the Delaware River basin is glaciated, and in the southern part many of the soils and zones of weathered rock are relatively thick and permeable.

Likewise, the value of about 3/4 mgd per square mile for ground-water recharge in the Pomperaug River basin probably is somewhat lower than the average for the Highlands in the Delaware River basin; in any case, an estimated average rate of recharge of 3/4 mgd per square mile for the highlands appears to be conservative. A similarly conservative estimate for the recharge to the aquifers of the Coastal Plain, which generally have more permeable intake areas than those of the consolidated-rock aquifers, gave a value of 1.1 mgd square mile (p. 37-39).

Because of the relatively low productivity and small storage capacity of most of the aquifers, and also because of many practical limitations, chiefly economic, only a small part of the ground-water discharge at natural outlets in the Appalachian Highlands can be diverted for man's use. However, pumpage substantially in excess of the 1955 rate of 130 mgd doubtless could be maintained with increased ground-water development, especially in the glacial outwash deposits in the major valleys, where induced recharge from streams is a significant factor.

The estimated recharge rate of 3/4 mgd per square mile is, of course, an average for the entire Appalachian Highlands; rather large variations from the average are to be expected. Data developed by the U. S. Geological Survey and the U. S. Weather Bureau indicate that precipitation in the area ranges from about 42 to 60 inches per year (2.0 - 2.9 mgd per sq mi); water loss ranges from about 17 to more than 28 inches per year (0.8 - 1.3 mgd per sq mi); and runoff ranges from 15 to about 42 inches per year (0.7 - 2.0 mgd per sq mi).

The area of the Appalachian Highlands in the Delaware River basin is about 9,700 square miles; thus, at an average rate of 3/4 mgd per square mile, the total ground-water recharge or discharge averages about 7,300 mgd. Most of this water moves relatively short distances through the weathered and fractured rocks within a few hundred feet of the land surface to discharge outlets in stream channels, springs, seeps, lakes, ponds, marshes, and low-lying areas where the saturated zone is sufficiently near the land surface to allow discharge by evapotranspiration. As in the Coastal Plain, the potential ground-water supply is assumed to equal the ground-water discharge to streams--an estimated 4,400 ± 500 mgd. However, because of the low permeability and small storage capacity of most of the hard-rock aquifers, and also because of other practical limitations, chiefly economic, the writers believe that only a small fraction of the potential supply can be developed feasibly and that development of surface supplies will continue to be dominant in the Highlands. However, large ground-water supplies may be developed locally, as in the glacial outwash along major streams in the glaciated part of the region.

Discharge through pumped wells is only a small fraction of the total ground-water discharge; about 130 mgd is being withdrawn at present. This discharge does not include pumpage from mines and quarries, whose unknown total may equal or exceed all withdrawals from wells for direct use.

GROUND-WATER STORAGE

The aquifers in the Appalachian Highlands range widely in their capacity to store water. As ground-water reservoirs, the deposits of glacial outwash in the major stream valleys compare favorably with the coarsest-grained aquifers in the Coastal Plain, whereas most of the consolidated-rock aquifers, which make up the bulk of the water-bearing materials in the Highlands, have relatively little storage capacity.

In the outwash, some of the beds of gravel and sand probably have specific yields exceeding 30 percent. However, in consolidated-rock aquifers specific yields of more than 2 percent probably are uncommon, except in the upper part of the weathered zone. In most consolidated rocks the specific yield decreases markedly with depth, and most of the usable storage capacity is in the weathered and highly fractured material near the land surface. Therefore, although the storage capacity of the consolidated rocks is much less than that of the unconsolidated sediments, the storage in some of the shallow, weathered and fractured rocks that provides the base, or fair-weather, flow of streams is comparable to that in many of the unconsolidated sediments.

Lack of adequate storage capacity is most likely to be an important limiting factor in ground-water development in moderately permeable aquifers having relatively low specific yields, such as the aquifers in the Brunswick formation of Triassic age.

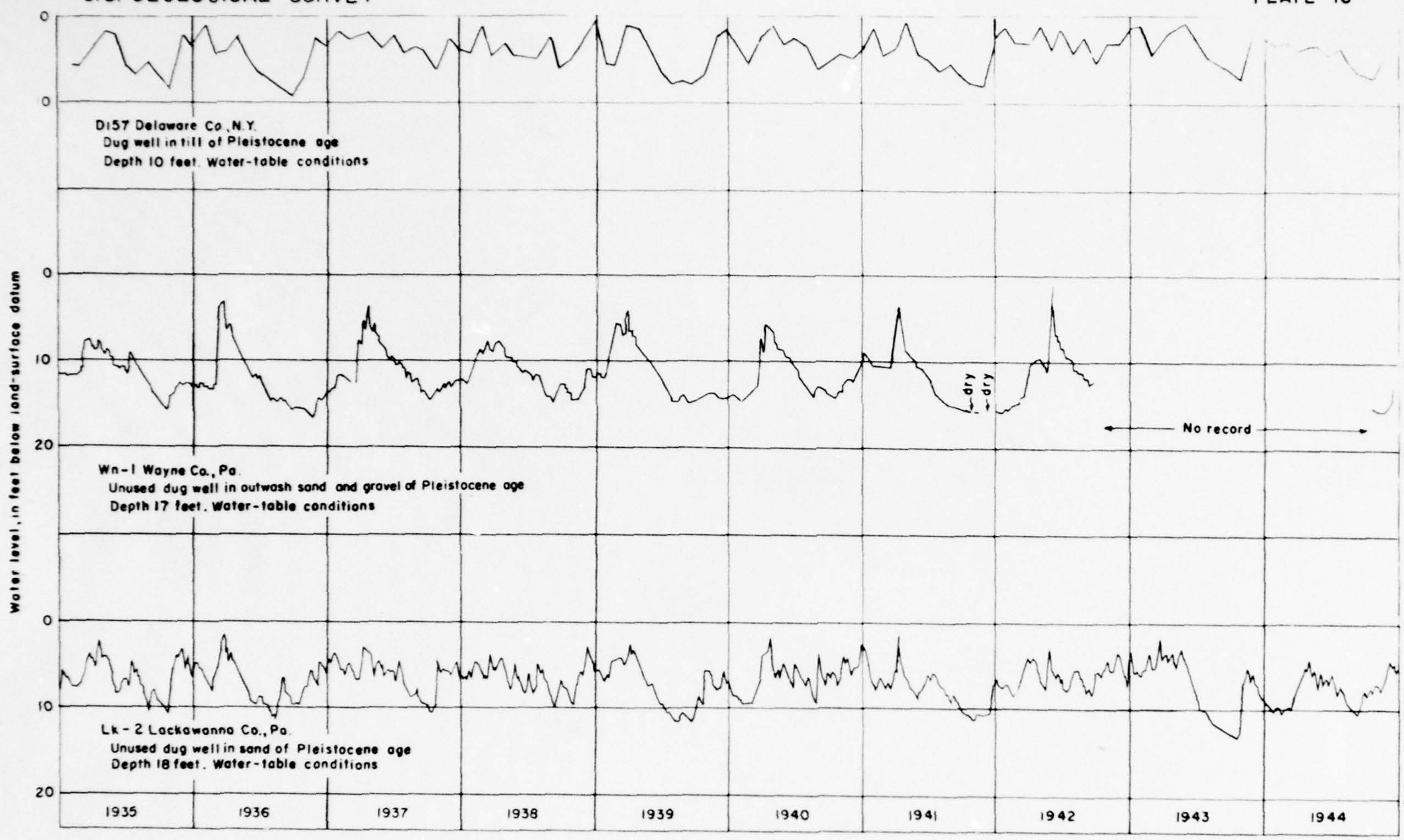
Some of the larger masses of glacial outwash store considerable volumes of water. One of the largest masses is that along the Delaware River from below Milford, Pa., to Port Jervis, N. Y., thence along the Neversink River and Basher Kill to Summitville, N. Y. From Milford to Summitville the length of the outwash body is 28 miles, its width averages a little less than a mile, and its average thickness is between 100 and 150 feet. The total volume of the saturated materials, then, is estimated to be 150,000 feet x 5,000 feet x 100 feet = 75 billion cubic feet. If the specific yield of the outwash is estimated conservatively to be 15 percent, its storage capacity is about 11 billion cubic feet, or about 80 billion gallons.

Only by diverting all or nearly all the streamflow from the valley during periods of pumping could a sizable portion of this ground-water storage capacity be used, however. So long as the streamflow is sufficient to supply, by induced recharge, a large part of the water pumped by wells in the valley, the greater part of the outwash will remain saturated.

The character of fluctuations in ground-water storage in glacial deposits is shown in the hydrographs of three unused shallow wells (pl. 16). The fluctuations in all three wells are believed to be entirely the result of changing rates of natural recharge and discharge. The peak water levels in the spring reflect high rates of recharge from rain and melting snow; the low water levels in the summer and autumn result from high evapotranspiration losses and hence lack of infiltration to the ground-water body. The average yearly water-table fluctuations in the three wells are from about 5 to 10 feet; because of the lack of specific-yield data for the materials penetrated by the wells, the changes in ground-water storage indicated by the fluctuations are not known.

CHEMICAL CHARACTER OF GROUND-WATER SUPPLIES

The formations of the Appalachian Highlands yield water with a wide variety of chemical characteristics. The concentrations of dissolved solids in individual samples analyzed ranged from 11 to 1,500 parts per million, and hardness from 4 to 660 ppm, measured as $CaCO_3$. The pH of individual samples ranged from 4.4 to 8.9. The formations of the Appalachian Highlands that contain water of highest quality are the glacial outwash in the New York part of the basin, the Catskill formation in northeastern Pennsylvania, and the Wissahickon formation in southeastern Pennsylvania. A few representative chemical analyses of ground water are given in tables 9 and 10.



FLUCTUATIONS OF WATER LEVELS IN REPRESENTATIVE WELLS IN UNCONSOLIDATED SEDIMENTS OF GLACIAL ORIGIN IN NORTHERN PART OF DELAWARE RIVER BASIN

Unconsolidated Sediments of Glacial Origin

Water from glacial deposits in the Delaware River basin is soft to moderately hard and in general is not highly mineralized. The iron content is usually low but in some places is objectionably high. Shallow wells may be contaminated from surface sources. Where pumping is heavy enough to induce recharge from adjacent streams a considerable part of the pumped water is derived from the streams, and the water is usually of better quality than the native ground water. Rima (written communication, 1957) has prepared table 11 summarizing 24 analyses of water from the valley fill deposits in the central part of the Delaware River basin. In table 11 the values for constituents given have been taken from available data and are not necessarily balanced analyses. Water from the valley fill generally is slightly acid. A few samples had excessive concentrations of iron, and some had very high concentrations of nitrate and chloride, perhaps owing to contamination from barnyards or cesspools.

Source and description of samples referred to by number in table 9:

Unconsolidated sediments of Appalachian Highlands

1. Near Pocono Lake Preserve, Monroe County, Pa., Pocono Lake Preserve springs; sodium plus potassium and dissolved solids calculated.
2. Newfoundland, Wayne County, Pa., Dairymen's League well; sodium plus potassium and dissolved solids calculated.
3. Port Jervis, Orange County, N. Y., Diamond Dairy well; analysis by New York State Department of Health.
4. Narrowsburg, Sullivan County, N. Y., Narrowsburg Water Department well; analysis by New York State Department of Health.
5. Hancock, Delaware County, N. Y., Hancock Water Co. well; analysis by New York State Department of Health.
6. Bloomville, Delaware County, N. Y., McIntosh Slaughter House well; aluminum 0.6.

Source and description of samples referred to by number in table 10:

Martinsburg shale

1. Near Newside, Lehigh County, Pa., P. J. German well.
2. Near Laurys, Lehigh County, Pa., H. Moyer well.

Catskill formation

3. Near Clamtown, Schuylkill County, Pa., K. Shellhamer well; color 3.
4. Honesdale, Wayne County, Pa., Dairymen's League well.

Source and description of samples referred to by number in table 10--Continued

Lockatong formation

5. Plumstead Township, Bucks County, Pa., Camp Ockanickon, Boy Scouts of America well; color 3.
6. Lower Makefield Township, Bucks County, Pa., G. K. Balderston-H. R. Bradley well; color 1.

Stockton formation

7. Phoenixville, Chester County, Pa., Phoenix Iron and Steel Co. well; color 2.
8. Norristown, Montgomery County, Pa., Handway and Gordon Dairy well; color 2.
9. Doylestown, Bucks County, Pa., Doylestown Borough well 8; color 2.
10. Doylestown, Bucks County, Pa., Doylestown Ice Co. well 2; color 3.
11. Newton, Bucks County, Pa., Newtown Artesian Water Co. well 3; color 3.
12. Trenton, Mercer County, N. J., New Jersey State Hospital well 8; color 4.
13. Skippack, Montgomery County, Pa., Walter Dinse well; color 3.
14. Near Quakertown, Bucks County, Pa., Quakertown Borough well 9; color 3.
15. Near Perkasie, Bucks County, Pa., Perkasie Water Supply Co. well 5, color 3.
16. New Hope, Bucks County, Pa., Universal Paper Bag Co., well; color 3.

Carbonate rocks

18. Near Lancaster, Lancaster County, Pa., J. P. Brenneman well; Conestoga limestone.
19. Buckingham, Bucks County, Pa., General Greene Inn well; Conococheague limestone.
20. Near Colesville, Lehigh County, Pa., R. C. Eveland well; Beekmantown group.
21. Center Valley, Lehigh County, Pa., M. DeFiore well; Tomstown dolomite.
22. Near Fogelsville, Lehigh County, Pa., Lehigh Portland Cement Co. well; Jacksonburg limestone.

Diabase

23. Green Lane, Montgomery County, Pa., Montgomery County Park well; color 4.
24. Near Sellersville, Bucks County, Pa., Sellersville Borough well 1; color 3.
25. Milford Square, Bucks County, Pa., Milford Square Pants Co. well; color 2.

Source and description of samples referred to by number in table 10--Continued

Gneiss

26. Near Kennett Square, Chester County, Pa., E. Fahey well; Baltimore gneiss.
27. Langhorne Manor, Bucks County, Pa., Langhorne Spring Water Co. well 2; color 3, Baltimore gneiss.
28. Near Yardley, Bucks County, Pa., Yardley Water and Power Co. well 5; Baltimore gneiss, color 2.
29. Near Shimersville, Lehigh County, Pa., Kings Highway Elementary School well; Byram granite gneiss.
30. Near Center Valley, Lehigh County, Pa., K. A. Beers well; Pochuck gabbro gneiss.

Chickies quartzite

31. Elverson, Chester County, Pa., Dolfinger Creamery well.
32. Langhorne Manor, Bucks County, Pa., Langhorne Spring Water Co. well 4; color 3.

Wissahickon formation

33. Centerville, New Castle County, Del., Winterthur Farm well.
34. Lincoln University, Chester County, Pa., Lincoln University well.
35. Brandywine Summit, Delaware County, Pa., W. C. Walton well.
36. Hulmeville, Bucks County, Pa., O.K.O. Plush Co. well; color 3.
37. Eddington, Bucks County, Pa., Publicker Industries well.

Table 11.--Summary of chemical analyses of 24 samples of ground water from valley fill

[Parts per million]

	Maximum	Average	Minimum
Silica (SiO_2)	20	11	5.1
Iron (Fe)	7.2	1.3	.01
Calcium (Ca)	57	22	4.1
Magnesium (Mg)	43	13	3.4
Sodium + potassium (Na + K) (5 analyses)	7.0	4.3	1.2
Sodium (Na) (19 analyses)	76	16	3.1
Potassium (K) (19 analyses)	12	3.1	.9
Bicarbonate (HCO_3)	123	38	7.0
Sulfate (SO_4)	189	50	4.9
Chloride (Cl)	122	17	3.0
Fluoride (F)	.4	.2	.1
Nitrate (NO_3)	107	18	.5
Dissolved solids	716	202	63
Hardness as $CaCO_3$	319	92	18
Non-carbonate hardness as $CaCO_3$	276	62	12
Specific conductance (micromhos at 25°C)	1,090	267	82
pH	6.7	--	5.2
Temperature (°F)	60	55	47

Glacial outwash in the northern part of the basin contains water of much better quality than that of the valley fill. More than half the samples were soft and the remainder moderately hard. Iron is present locally, unpredictably distributed in the aquifers, but concentration is not excessive in most of the samples. Table 12, summarizing analyses of water from glacial outwash in the northern part of the basin, was prepared from data furnished by N. M. Perlmutter and E. H. Salvas (written communication, 1957). Water from the glacial outwash in the northern part of the basin is less mineralized and softer than water in the valley fill of the central part of the basin. So also is the quality of the stream water in the northern part of the basin better than that in the central part.

Table 12.--Summary of chemical analyses of ground water from glacial outwash

[Parts per million]

	Maximum	Median	Minimum	Number of Samples
Iron (Fe)	4.5	0.19	0.03	20
Manganese (Mn)	.28	.01	.01	12
Bicarbonate (HCO_3)	117	33.5	15	18
Sulfate (SO_4)	27	9.3	4	11
Chloride (Cl)	20	4.4	.4	19
Nitrate (NO_3)	2.0	1.4	.1	4
Dissolved solids	145	94	33	13
Hardness as $CaCO_3$	124	50.5	22	20
pH	7.9	6.8	5.8	19

Clastic Rocks

Of the clastic formations in the Delaware River basin the Catskill, Stockton, and Brunswick are best known for the generally good quality of water yielded, and of these three, the best water is obtained from the Catskill formation. Its water is uniformly as good as, or better than, that obtained from the glacial outwash or from the crystalline rocks. Only a limited number of analyses are available for the remaining clastic aquifers, but from the available analyses it appears that the shale of the Mauch Chunk formation generally yields water that is soft and not highly mineralized. The Martinsburg shale, the Bloomsburg red beds, and the Middle and Upper Devonian marine beds contain water that is not highly mineralized but that ranges from soft to moderately hard. The waters of the Allegheny and Conemaugh formations are commonly polluted with acid mine drainage and even at some distance from mines have large concentrations of iron and sulfate resulting from the oxidation of pyrite. In 5 samples of water, for example, the iron concentration ranged from 2.0 to 0.8 ppm. The chemical character of the water contained in the Lockatong formation appears to be about the same as that in the Stockton and Brunswick formations.

Martinsburg Shale

Water from the Martinsburg shale is soft to moderately hard, the hardness being mostly of the noncarbonate type. A summary of the analyses of water from 9 wells and springs in Lehigh County, Pa., is presented in table 13 (Rima, D. R., written communication, 1957) and two representative analyses are given in table 10.

Table 13.--Summary of chemical analyses of 9 samples of ground water from the Martinsburg shale

[Parts per million]

	Maximum	Minimum
Sodium + potassium (Na + K)	5.3	0.9
Bicarbonate (HCO_3)	62	16
Sulfate (SO_4)	61	8.3
Chloride (Cl)	10	5.0
Nitrate (NO_3)	33	7.8
Hardness as $CaCO_3$	124	43
Non-carbonate hardness, as $CaCO_3$	89	29
Specific conductance (micromhos at 25°C)	320	121
Temperature (°F)	55	51
pH	7.7	6.3

Catskill Formation

The Catskill formation yields water of excellent quality, which is used for domestic, industrial and municipal supplies, generally without treatment. The water ranges from very soft to moderately hard and is commonly low in iron. A few deep wells in Wayne County give water containing small quantities of hydrogen sulfide. Table 14, prepared by D. R. Rima (written communication 1957), summarizes 18 chemical analyses of ground water from the Catskill formation; additionally two representative analyses are given in table 10.

Table 14.--Summary of chemcial analyses of 18 samples of ground water from the Catskill formation

[Parts per million]

	Maximum	Average	Minimum
Silica (SiO_2)	13	7.3	4.0
Calcium (Ca)	28	11.2	2.0
Magnesium (Mg)	7.2	3.5	1.0
Sodium (Na)	20	6.7	1.0
Potassium (K)	2.4	1.4	.5
Bicarbonate (HCO_3)	117	51.2	8.0
Sulfate (SO_4)	23	6.4	1.0
Chloride (Cl)	22	5.0	1.0
Nitrate (NO_3)	6.0	2.4	.1
Dissolved solids	176	74	22
Hardness as $CaCO_3$	97	44	9.0
Non-carbonate hardness, as $CaCO_3$	22	9.0	1.0
Specific conductance(micromhos at 25°C)	100	60	34
pH	7.4	--	6.2
Temperature (°F)	57	50	48

Stockton Formation

Water from the Stockton formation varies widely in its chemical characteristics. The water commonly has low to moderate concentrations of dissolved solids, generally less than 400 ppm. In the more highly mineralized samples sulfate constitutes a large proportion of the anions. This probably results from leaching local deposits of glauberite, a mineral with the chemical formula $Na_2SO_4CaSO_4$. Most of the samples tested range from moderately hard to hard. The very hard waters have a relatively large proportion of noncarbonate hardness; rarely is the concentration of iron objectionable. Table 15 compiled by D. R. Rima (written communication, 1957) summarizes a group of chemical analyses of ground water from the Stockton formation; six additional analyses regarded as typical are also given in table 10.

Table 15.--Summary of chemical analyses of 54 samples of ground water from the Stockton formation

[Parts per million]

	Maximum	Average	Minimum
Silica (SiO_2)	33	22	8.4
Iron (Fe)	2.3	.3	.04
Calcium (Ca)	233	41	2.5
Magnesium (Mg)	27	12	1.6
Sodium + potassium (Na + K) (42 analyses)	46	18	.7
Sodium (Na) (12 analyses)	37	16	8.1
Potassium (K) (12 analyses)	3.5	1.6	.5
Bicarbonate (HCO_3)	258	110	7.0
Sulfate (SO_4)	603	82	9.4
Chloride (Cl)	54	12	1.2
Fluoride (F)	1.1	.1	.1
Nitrate (NO_3)	48	11	.4
Dissolved solids	1,040	261	45
Hardness as $CaCO_3$	660	161	18
Non-carbonate hardness as $CaCO_3$	562	89	4
Specific conductance (micromhos at 25°C)	1,230	385	69
pH	8.5	--	6.0
Temperature (°F)	58	56	53

Brunswick Formation

The Brunswick formation produces water that is moderately mineralized and may range from soft to very hard. In samples the hardness is mostly of the non-carbonate type. The water is suitable for domestic, industrial and municipal use although softening or treatment to remove iron is often required. Water from the Brunswick formation was alkaline (pH 7.1 to 8.9) in all 23 samples, perhaps because of the calcareous sandstone and conglomerate associated with this aquifer. Table 16 was prepared by D. R. Rima (written communication, 1957) to summarize a number of chemical analyses of ground water in the Brunswick formation; also, four typical analyses are given in table 10.

Table 16.--Summary of chemical analyses of 23 samples of ground water from the Brunswick formation

[Parts per million]

	Maximum	Average	Minimum
Silica (SiO_2)	25	19	10
Iron (Fe)	1.8	.6	.03
Calcium (Ca)	190	67	15
Magnesium (Mg)	112	32	3.8
Sodium + potassium (Na + K) (6 analyses)	14	4.9	.6
Sodium (Na) (11 analyses)	76	18	2
Potassium (K) (11 analyses)	1.8	1.0	.2
Bicarbonate (HCO_3)	242	134	26
Sulfate (SO_4)	144	61	7.0
Chloride (Cl)	22	8.3	1.0
Fluoride (F)	.4	.2	.1
Nitrate (NO_3)	21	7.2	.4
Dissolved solids	386	297	217
Hardness as $CaCO_3$	284	171	46
Non-carbonate hardness as $CaCO_3$	158	54	10
Specific conductance (micromhos at 25°C)	594	406	172
pH	8.9	--	7.1
Temperature (°F)	56	53	51

Carbonate Rocks

Rainwater containing dissolved carbon dioxide is slightly acid and an excellent solvent for limestone and other carbonate rocks. Consequently the groundwater from the limestone formations in the Delaware River basin characteristically is moderately mineralized and hard. The chief mineral constituents are calcium and magnesium bicarbonates. Ground water from carbonate rocks in the Delaware River basin usually is slightly alkaline, low in iron, and of excellent quality except for its hardness. Table 17 summarizes 60 analyses of water from carbonate rocks in Pennsylvania. These include many of the 41 analyses for southeastern Pennsylvania discussed by Hall (1934, p. 42) and lead to much the same conclusions. Hall found also that only 2 of his 41 samples contained more than 1 ppm of iron and more than half contained less than 0.1 ppm of iron. Additional information is presented in table 10 giving analyses from 6 samples regarded as typical.

The ratio of calcium to magnesium in water from the Conestoga limestone is significantly greater than in waters from the Conococheague, Cockeysville, and other limestone formations. Water from the Cockeysville marble (4 samples) appears to be less mineralized than water from other limestone formations.

Table 17.--Summary of chemical analyses of 60 samples of ground water from carbonate rocks

[Parts per million]

	Maximum	Medium	Average	Minimum	Number of analyses
Silica (SiO_2)	33	13	13	4.7	53
Calcium (Ca)	107	57	58	5.6	34
Magnesium (Mg)	52	18	20	2.4	35
Sodium + Potassium(Na+K)	29	6.0	8.2	.9	30
Sodium (Na)	38	5.7	7.8	1.3	24
Potassium (K)	7.7	1.9	2.5	.6	24
Bicarbonate(HCO_3)	388	186	194	41	56
Sulfate (SO_4)	120	26	35	2.3	61
Chloride (Cl)	58	7.5	13	1.0	58
Nitrate (NO_3)	73	12	16	.0	60
Dissolved solids	609	245	280	75	35
Hardness as $CaCO_3$	508	201	208	24	56
Specific conductance (micromhos at 25°C)	633	356	369	138	27
pH	8.3	7.6	--	6.0	28

Crystalline Rocks

The crystalline rocks of Precambrian and early Paleozoic age in the Delaware River basin yield excellent water that is low in dissolved solids and hardness. See table 10 for typical sample analyses. With the exception of iron, which is locally present in excessive concentrations (more than 3 ppm in some samples), the water contains no objectionable mineral impurities.

Water samples from 4 wells in diabase, all near Quakertown, Pa., had from 66 to 398 ppm of dissolved solids, 32 to 272 ppm of hardness as $CaCO_3$, and 0.18 to 1.4 ppm of total iron. These are calcium and magnesium bicarbonate waters.

Samples of water from 4 wells and 1 spring in gneiss, in Bucks, Delaware, Lehigh, and Northampton Counties, Pa., had from 51 to 261 ppm of dissolved solids, 13 to 174 ppm of hardness as $CaCO_3$, and 0.03 to 0.74 ppm of iron. The samples with large concentrations of dissolved solids have large concentrations of nitrate or chloride also. This is probably indicative of contamination from barnyards or cesspools.

Table 18.--Summary of chemical analyses of 18 samples of ground water from crystalline rocks

[Parts per million]

	Maximum	Average	Minimum
Silica (SiO_2)	35	18	8.7
Iron (Fe)	3.4	.67	.02
Calcium (Ca)	22	12	2.9
Magnesium (Mg)	9.9	5.3	1.3
Sodium (Na)	21	8.6	2.2
Potassium (K)	4.4	2.2	.4
Bicarbonate (HCO_3)	106	35	8.0
Sulfate (SO_4)	48	20	.3
Chloride (Cl)	40	10	1.0
Fluoride (F)	.2	.1	0
Nitrate (NO_3)	34	12	.3
Dissolved solids	246	118	51
Hardness as $CaCO_3$	108	55	13
Non-carbonate hardness as $CaCO_3$	71	27	0
Specific conductance (micromhos at 25°C)	384	167	64
pH	7.9	--	5.2
Temperature (°F)	58	54	52

Wissahickon Formation

Good water is obtained from the Wissahickon formation in Pennsylvania and Delaware. The water is not highly mineralized, unless contaminated; 10 or 12 samples contained less than 100 ppm of dissolved solids. The water is soft or only moderately hard, with low chloride concentration. Three samples from Delaware County, Pa., and 1 from Bucks County, Pa., contained excessive concentrations of iron, but 7 of the 12 samples contained less than 0.3 ppm of iron. The harder waters generally have the higher concentrations of sulfate. According to Hall (1934, p. 27) excessive hardness is sometimes due to pegmatite dikes which contain large percentages of lime-soda feldspar. On the whole, however, the water contained

in the Wissahickon formation is uniformly of good quality. Springs in the Wissahickon formation on occasion become polluted, as in the fall of 1957 when (Philadelphia Inquirer, 10/10/57) 75 springs issuing from the Wissahickon formation in Fairmount Park, Philadelphia, Pa., were posted (closed for use). Pollution of these springs in a highly residential neighborhood probably stems largely from leaky sewers. In table 19 are summarized 16 analyses of water from the Wissahickon formation, and in table 10 are 6 analyses that are regarded as representative of the formation.

Table 19. - Summary of chemical analyses of 16 samples of ground water from the Wissahickon formation
[Parts per million]

	Maximum	Median	Average	Minimum	Number of samples
Silica (SiO_2)	36	20	20	7.3	12
Iron (Fe)	8.7	.22	1.8	.04	12
Calcium (Ca)	14	6.1	7.9	3.4	12
Magnesium (Mg)	8.3	3.6	3.9	1.7	12
Sodium (Na)	8.3	5.6	5.1	2.8	11
Potassium (K)	2.8	1.6	1.6	.7	11
Bicarbonate (HCO_3)	70	31	35	8.5	16
Sulfate (SO_4)	60	10	19	2.7	16
Chloride (Cl)	16	5.3	5.6	1.8	16
Nitrate (NO_3)	34	6.6	8.7	.3	12
Dissolved solids	154	73	80	40	12
Hardness as $CaCO_3$	102	44	47	17	15
pH	6.9	6.3	--	5.9	7

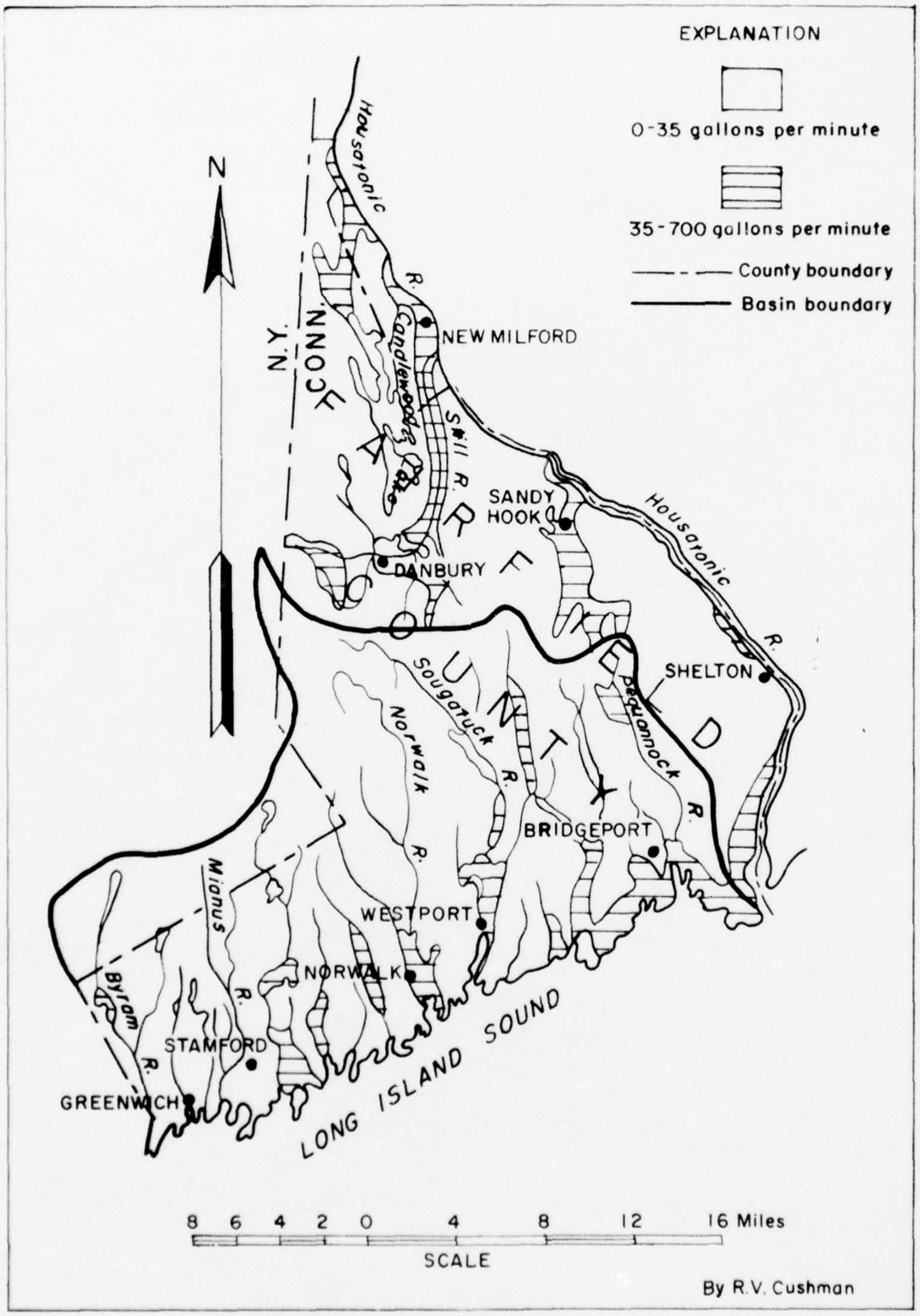
IN THE SERVICE AREA OUTSIDE THE BASIN

FAIRFIELD COUNTY, CONNECTICUT

by R. V. Cushman

Introduction

Fairfield County occupies an area of about 633 square miles in southwestern Connecticut that is bounded chiefly by Long Island Sound, the Housatonic River and the New York State border (pl. 17) The estimated 1957 population of 597,900 for the county is largely



MAP OF FAIRFIELD COUNTY, CONN., SHOWING THE COASTAL BASINS, AND EXPECTED YIELDS OF WELLS, BY AREAS

urban and suburban and is engaged in industrial and commercial activities. Bridgeport, Stamford, Danbury, and Norwalk are the largest cities. The increasing demands for water by the growing population and expanding industry of Fairfield County are responsible for its being placed within the service area of the Delaware River basin. It is estimated in a report of the Connecticut Water Resources Commission (1957) that the county will have a demand for 152.2 million gallons of water daily by the year 2000.

Principal sources of published information on the water resources, especially on the ground water of Fairfield County, are given by Gregory and Ellis (1916); Palmer (1920); Leggette and others (1938); Rodgers, Gate, Cameron and Ross (1956); New England-New York Interagency Commission (1954); and Connecticut Water Resources Commission (1957).

Considerable unpublished information is available from the U. S. Geological Survey and the Connecticut Geological and Natural History Survey.

Physical Features

The surface of Fairfield County is generally a low rolling plain sloping gradually southward to Long Island Sound. The terrain is typically flat within a narrow coastal strip along Long Island Sound but is rolling and deeply dissected by major streams for the remaining area. The northeastern third of the county is within the drainage basin of the Housatonic River. Most of the remainder of the county is drained by coastal streams of which the most important are the Byram, Mianus, Norwalk, Pequonnock, and Saugatuck Rivers. The largest of these is the Saugatuck.

General Geology

The area is underlain by a wide variety of consolidated rocks consisting chiefly of gneiss, granite gneiss, schist, and dolomitic marble, all of pre-Carboniferous age. The distribution of the several bedrock units is shown on the preliminary geologic map of Connecticut (Rodgers and others, 1956). The bedrock, though consisting of rocks of different kinds, is generally dense, compact, and has a low porosity; however, it is broken by joint openings which provide the available space for ground-water storage and transmission.

The bedrock is exposed at numerous places, but elsewhere it is overlain by glacial deposits of the Pleistocene epoch. These unconsolidated glacial materials consist of unstratified till and stratified drift or outwash. The till consists of a mixture of boulders, sand, silt, and clay lacking sorting and bedding. It

lies directly on the bedrock and ranges in thickness from a few inches to as much as 50 or 60 feet. It usually has a low permeability owing to its unsorted character, the small rock particles filling spaces between larger ones.

The stratified drift consists of irregularly bedded deposits of gravel and sand and minor amounts of silt and clay; the entire sequence was deposited by melt water from glacial ice sheets. Because of the sorting action of flowing waters, stratified drift generally transmits water readily and is the most permeable of the aquifers in the county. The stratified drift occurs chiefly in valleys where it may have a thickness exceeding 100 feet, but it occurs also as a thin patchy veneer over many of the coastal flats bordering Long Island Sound. Generally the areas underlain by stratified drift are essentially the same as those shown by horizontal ruling on the map (pl. 17). The most extensive deposits are those bordering Long Island Sound and the Housatonic River in the vicinity of Bridgeport, and those underlying the Still River valley in the Danbury-New Milford area.

Ground-Water Sources

The principal sources of ground water in Fairfield County are the bedrock formations and the unconsolidated glacial deposits.

Because the bedrock is dense and compact, ground water is stored in, and moves mostly along, joint cracks and other similar fracture openings. Therefore, the success of a well drilled in bedrock depends upon whether it taps open fractures filled with water, and whether such openings are interconnected in a sizable volume of rock. These openings are distributed in such a haphazard manner that it is generally not possible to predict in advance of drilling where the greatest yield of water can be obtained. Information on the yields of drilled wells in bedrock in Fairfield County is available from the published data and from a large number of well-completion reports filed with the State Water Resources Commission by well drillers in the area. The reported yields of individual wells range from less than 1 gpm (1,440 gpd) to a maximum of 100 gpm (144,000 gpd); however, if a well yielding 100 gpm initially were pumped over a considerable length of time the yield quite likely would decrease. The average yield is about 8-10 gpm, which is sufficient for most domestic supplies. Little difference is noted in the water-bearing capacity of the several bedrock units, even the dolomitic marble shows about the same yields as other crystalline rocks. Thus, although the crystalline bedrock is widely used as a source of domestic water supply because of its widespread occurrence in the county, it may be expected to yield quantities of ground water sufficient only for small municipal, industrial, and

agricultural supplies. A number of industrial plants in Bridgeport and Stamford augment water purchased from municipal supplies with ground water from drilled wells in bedrock. Heavy pumping from a number of these wells located close to tidewater has resulted in a local increase in the chloride content of the ground water.

The quality of natural ground water from bedrock is adequate for most purposes. The water generally is only moderately hard, although water from the dolomitic marble may be hard to very hard.

Wells in the glacial till in Fairfield County generally yield less than 3 gpm. Because of its widespread occurrence in upland sections it is an important potential source of small water supplies for domestic and stock uses. These supplies are commonly obtained from dug wells. Throughout much of the area, however, the till is thin, of small storage capacity, and of low permeability; therefore it furnishes rather undependable supplies. Consequently the general practice is to drill through the till into the underlying bedrock for water.

The deposits of stratified drift, where they consist of sand and gravel, are by far the most important water-bearing formations in Fairfield County, and are potential sources for additional water supplies for agriculture, industries, and small municipalities. The sand and gravel are quite permeable and readily absorb and store a large percentage of the local precipitation. The expectable yield of modern large-diameter drilled wells, within the more promising areas shown in plate 17 is generally between 100 and 500 gpm, although yields either greater or smaller than the limits indicated have been measured. These areas have not been tested sufficiently to permit an accurate areal evaluation of well yields, and particularly of sustained yields. Where finer grained materials predominate in the deposits, wells may yield less than the limits given, but where the deposits are composed of coarse-grained sand and gravel, properly constructed wells may yield a million gallons a day or more. Where the wells are favorably located with respect to sources of recharge such as perennial streams, long-term, high, sustained yields may be expected. For example, several wells of the Bridgeport Hydraulic Co., that penetrate sand and gravel deposits adjacent to the Housatonic River in Shelton, are reported to have been pumped at rates exceeding 700 gpm (1 mgd) per well for long periods. These wells are used to augment the extensive surface-water supply system for the Bridgeport area. Insofar as is known, ground water in stratified drift in most of the valleys is in hydraulic continuity with adjacent streams. Ordinarily, of course, ground water in these deposits moves toward and sustains the flow of the streams, but where heavy pumping occurs in aquifers near the streams the hydraulic gradient may be reversed and the river water flows from the streams toward the wells.

Table 20.--Summary of water-resources values by counties in New York and Connecticut part of Delaware River service area

County and State	Area	Average annual precipitation, P				Average annual runoff, R				Average annual evapotranspiration, Et			
	sq mi	in.	mgd[1]	mgd/sq mi	bgy[2]	in.	mgd[1]	mgd/sq mi	bgy[2]	in.	mgd[1]	mgd/sq mi	bgy[2]
Fairfield Conn.	633	48	1,400	2.24	520	26	770	1.2	280	22	650	1.0	240
Dutchess N. Y.	816	42	1,600	1.96	580	18	690	0.8	250	24	900	1.1	340
Orange N. Y.	846	44	1,700	2.05	630	20	790	0.9	290	24	950	1.1	340
Putnam N. Y.	235	46	500	2.13	180	24	260	1.1	95	22	240	1.0	85
Rockland N. Y.	201	44	410	2.05	150	21	200	1.0	72	23	220	1.1	78
Ulster N. Y.	1,172	48	2,600	2.24	960	30	1,600	1.4	600	18	990	0.8	360
Westchester N. Y.	487	48	1,100	2.24	400	26	590	1.2	220	22	500	1.0	180
Totals	4,390	46	9,300	2.12	3,400	24	4,900	1.1	1,800	22	4,500	1.0	1,600

1/ Million gallons a day over entire county
2/ Billion gallons a year

Heavy pumping from wells adjacent to streams that are polluted or close to tidewater may, therefore, induce water of undesirable quality to move into fresh ground-water bodies and adversely affect their use for most purposes. This has taken place where wells penetrating outwash in the coastal area of Bridgeport have been pumped heavily.

The quality of natural ground water from stratified drift or outwash is suitable for most uses; however, the iron concentration may be somewhat high in some localities.

Magnitude of Water Supply

Ground water of Fairfield County is practically all derived from rainfall and snowmelt of local precipiation. About 48 inches of precipitation falls annually in the county, amounting to an average of about 1,400 mgd or 0.520 tgy. Of this, 26 inches, or 0.280 tgy is discharged as direct and ground-water runoff in streams; the rest, 22 inches, or about 0.240 tgy is lost by evapotranspiration. This assumes, of course, no storage changes of consequence in ground water or soil moisture. Of the 0.280 tgy runoff, about half is discharged as storm (direct) runoff and the remainder appears as base flow in the streams (table 20).

Public Water-Supply Systems Using Ground Water

At the present time, a number of smaller community systems in the Housatonic River basin part of Fairfield County are supplied entirely from ground water. These systems generally furnish less than 35 gpm to their consumers, although the State Hospital at Newtown is reported to pump about 350 gpm. Several of the large public water-supply systems pump ground water to augment surface-water sources during periods of peak demand and low flow. The largest of these is the Bridgeport Hydraulic Co., which has a number of wells located throughout its franchise area.

DUTCHESS, ORANGE, PUTNAM, ROCKLAND, ULSTER, AND WESTCHESTER COUNTIES, NEW YORK

by N. M. Perlmutter

Introduction

Dutchess, Orange, Putnam, Rockland, Ulster, and Westchester Counties together comprise an area of about 3,760 square miles in southeastern New York (pl. 18 and table 20). With the exception of small parts of Ulster and Orange Counties, which lie in the Delaware River basin, the area is entirely in the adjoining Hudson River basin. Some of the counties are relatively densely populated and use substantial quantities of ground water. Owing to their

potentialities for increase in population and corresponding increase in water use, these counties are considered to be within the service area of the Delaware River basin. Accordingly, a brief summary of ground-water conditions and of the total water resources within these counties is pertinent to the overall investigation of the water resources of the Delaware River basin.

Table 20, which summarizes water-resources values for this part of the service area (including Fairfield County, Conn.) shows that on an average annual basis approximately 46 inches of rain, and snow equivalent to rain, falls on nearly 4,400 square miles of these counties in New York and Connecticut. This is about equal to 9,300 mgd, or 3.4 tgy. However, about 22 inches is lost by evapotranspiration. This amounts to about 1.6 tgy. The rest of the precipitation, about 24 inches, or about 1.8 tgy runs off in the streams.

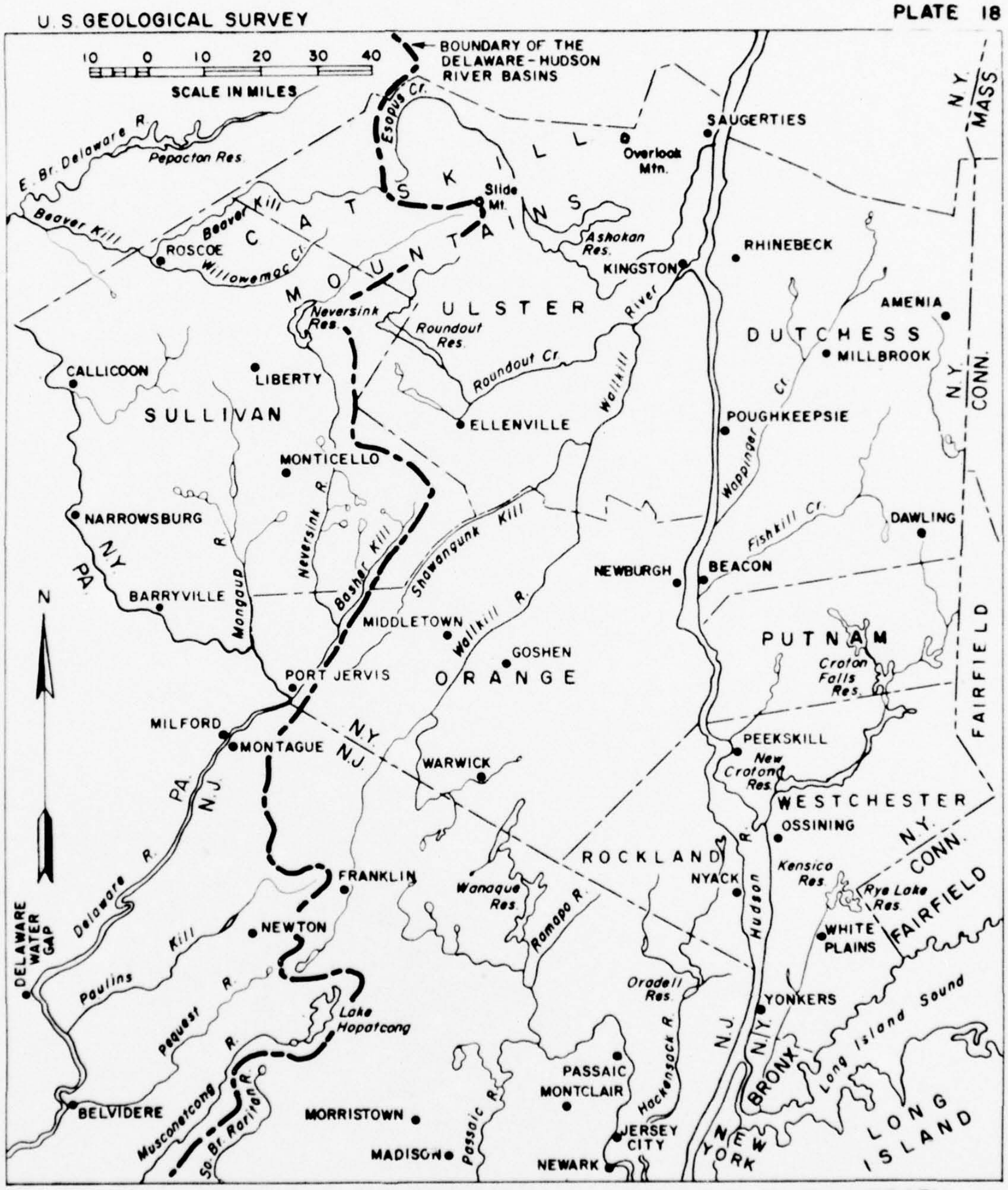
Asselstine and Grossman (1955) and Grossman (1957) have prepared published reports for two of the counties in New York, Westchester and Putnam. Reports are in preparation by the U. S. Geological Survey for Dutchess and Rockland Counties, but no investigations have been started in Orange and Ulster Counties. A considerable amount of unpublished ground-water and geologic data on these counties is in files of the U. S. Geological Survey either at Albany or at Mineola, N. Y. The following descriptions of the general geology and water-bearing characteristics of the aquifers in each county are based partly on examination of miscellaneous unpublished data of the Geological Survey, published bulletins of the New York State Water Power and Control Commission, and of the New York State Museum, the geological map of New York State (Merrill, 1901), and field observations of the writer, particularly in Rockland and Orange Counties.

Dutchess County

Dutchess County contains approximately 816 square miles. The permanent population was 137,000 in 1950 and about 158,000 in 1955. The land surface in most of the county is a gently rolling plain ranging in altitude from about sea level along the Hudson River to about 500 feet in the interior. The southern border of the county is formed by the Hudson Highlands, a part of the New England Upland (pl. 3), which reaches an altitude of more than 1,600 feet.

General Geology

Dutchess County is underlain by igneous, metamorphic, and sedimentary rocks ranging in age from Precambrian to Ordovician. The rocks are closely folded and have a northeasterly strike.



MAP OF METROPOLITAN NEW YORK AND ADJACENT PART OF NEW JERSEY

The main bedrock units are: (1) undifferentiated granite, gneiss, and diorite of Precambrian age which crop out mainly along the southern border of the county; (2) an argillaceous (clayey) unit historically known as the Hudson River formation (now abandoned) which, as defined (Vanuxem, 1842) in this county, includes shale, slate, phyllite, and schist of the Nassau and Schodack formations of Early Cambrian age, and the Deepkill and Normanskill formations of Ordovician age; and (3) scattered elongate belts of the Cheshire quartzite of Early Cambrian age, and the Stockbridge limestone, a metamorphosed carbonate rock formation of Cambrian and Ordovician age. The Hudson River formation of former usage is the most widely distributed bedrock unit which occurs in the Valley and Ridge province as a northward extension of the Great Valley in Pennsylvania (pl. 3). Unconsolidated deposits of till and outwash of Pleistocene age cover most of the bedrock surface, being thinner on the uplands and deeper in the valleys.

Water-bearing Characteristics of the Deposits

Ground water occurs in the till, outwash, and bedrock. Deposits of till range in thickness from less than a foot to 100 feet or more. Yields of wells in till average only a few gallons per minute. Deposits of outwash composed of sand and gravel yield the largest quantities of water. Most of these deposits are restricted to major valleys. Yields of 34 wells screened in outwash range from 10 to 600 gpm and average about 100 gpm. Where in hydraulic continuity with the valley streams, the outwash deposits are capable of sustained high yields.

About 90 percent of the existing wells tap the Hudson River formation of former usage or the Stockbridge limestone. Yields of 439 wells tapping the Hudson River formation of former usage range from 0 to 300 gpm and average about 19 gpm. Yields of 153 wells tapping the Stockbridge limestone range from 0 to 220 gpm and average about 22 gpm. Yields from the other bedrock units average about 12 gpm.

Public-supply systems serve approximately one-half the population of Dutchess County. Most of the water used is taken directly from surface-water sources. Sixteen public-supply systems tap ground-water sources wholly or in part, but some of the yield from wells is derived from streams as induced recharge where well-pumping influences (cones of depression) reach stream courses.

Magnitude of Water Supply

Nearly all the ground water is derived from precipitation within the county. One inch of rain, or of snow having a water content equivalent to 1 inch of rain, falling on 1 square mile yields about 17 million gallons of water. Thus, with an average precipitation of about 42 inches falling on the 816 square miles of Dutchess County,

a total of 1,600 mgd or about 580,000 million gallons of water is received each year. Of this, 18 inches, or about 0.250 tgy becomes runoff; and 24 inches, or about 0.340 tgy is lost as evapotranspiration. In the above estimates it is assumed that changes of water storage in the area are negligible. This is reasonable because, over a long enough period of time (base period for these estimates is 40 years), changes in storage balance out at or near zero.

Orange County

Orange County contains an area of about 846 square miles. The permanent population in 1950 was about 152,000 and in 1955 was about 168,000. The land surface in Orange County consists of four main types: (1) a broad, gently rolling plain in the central part of the county generally ranging in altitude from a few feet above sea level along the Hudson River to about 1,000 feet; (2) a dissected highlands area to the southeast where land surface reaches an altitude of more than 1,500 feet; (3) a narrow northeasterly trending belt of ridges and valleys bordering the plain on the northwest; and (4) a small plateau area in the extreme northwestern corner of the county.

General Geology

Orange County is underlain by consolidated igneous, metamorphic, and sedimentary rocks ranging in age from Precambrian to Devonian. The rocks are folded and strike northeasterly. Dips are gentle to steep. Major faults occur in some areas. The central two-thirds of the county is underlain by gray slaty shale and sandstone comprising the Normanskill shale and the Snake Hill formation of Middle Ordovician age. To the southeast the rocks of the Normanskill shale are in contact with elongate belts of infolded and faulted beds of limestone of Precambrian, Cambrian, and Ordovician age, and sandstone, conglomerate, and shale of Devonian age. These rocks in turn lie on and against the complex crystalline rocks of the Highlands area which consist mainly of granite and gneiss. The beds of the Normanskill and Snake Hill are overlain unconformably to the northwest by the northwesterly dipping rocks of the Shawangunk conglomerate and High Falls shale of Silurian age which form Shawangunk Mountain. The prominent valley which parallels the northwest flank of Shawangunk Mountain is underlain by northwesterly dipping beds of limestone, shale, and sandstone comprising a number of formations ranging in age from Late Silurian to Middle Devonian. The plateau area to the northwest is underlain by sandstone and shale of Middle to Late Devonian age.

The bedrock in most of the county is covered by a mantle of unconsolidated deposits of Pleistocene age composed of till and outwash.

Water-Bearing Characteristics of the Deposits

Records for about 200 wells and springs in Orange County are available in the files of the U. S. Geological Survey. Most of the data were obtained in the extreme northwestern part of the county with some scattered data from other parts. Thus a detailed appraisal of the ground-water conditions requires considerably more field work than has been accomplished to date.

The water-bearing deposits are till, outwash, and bedrock. The till covers the upland areas throughout most of the county, and generally yields small quantities sufficient for domestic use to dug wells. Deposits of outwash sand and gravel as much as several hundred feet thick occur in many of the stream valleys and lowland areas. The largest body of outwash occurs in the Port Jervis trough area (chiefly in the valleys of Neversink River and Basher Kill) in the northwestern part of the county. The gravels and sands of this body have a maximum thickness of more than 200 feet and constitute a very large underground natural storage reservoir. Other deposits of outwash are relatively untapped and generally are potential sources of substantial quantities of water. Where such deposits are in hydraulic continuity with perennial streams their yields are high and sustained, for water pumped from wells in these deposits may be largely replaced in the aquifer by induced recharge from the streams. The yields of 13 wells screened in outwash range from about 3 to 380 gpm and average about 85 gpm. Larger yields doubtless are available in many places.

Most of the wells in the county are drilled into bedrock. The main bedrock aquifer is the Normanskill shale. Yields of 16 wells penetrating the Normanskill range from about 2 to 80 gpm and average about 30 gpm. Yields of 21 wells in sandstone and shale of Devonian age range from about 1 gpm to 80 gpm and average about 20 gpm. Yields of wells tapping limestone of Cambrian and Ordovician age are among the highest for bedrock aquifers. In 11 wells, the yields range from about 20 to 150 gpm and average about 80 gpm. Wells in granite and gneiss have the lowest yields. In 10 wells, the yields range from about 1 to 25 gpm and average about 10 gpm.

Approximately 90 percent of the water pumped in the county is from surface-water sources. Thirty public-supply systems ranging from small real estate developments to municipalities, pump water wholly or in part from wells and springs. Ground water is also used for domestic, agricultural, and some industrial purposes.

Magnitude of Water Supply

Ground water within the county is derived almost entirely from precipitation falling on its 846 square miles of the area. Receiving an average of about 44 inches of precipitation a year, the total rainfall amounts to about 1,700 mgd or 0.630 tgy. Of this, 20 inches or about 0.290 tgy becomes runoff and the rest, 24 inches or about 0.340 tgy, assuming no essential water-storage change in the aquifers and soil, is lost by evapotranspiration.

Putnam County

From a report by Grossman (1957) on the ground-water resources of Putnam County most of the following data are summarized.

Putnman County contains an area of 235 square miles. The permanent population in 1953 was about 20,000 and in 1955 was about 28,000. The county is in the Hudson Highlands, a dissected belt of low mountains which rise from about sea level along the Hudson River to as much as 1,400 feet in the upland areas. Valleys in the Highlands generally are narrow and straight.

General Geology

The bedrock underlying Putnam County consists of folded and faulted consolidated igneous and metamorphic rocks ranging in age from Precambrian to Ordovician. More than 90 percent of the bedrock is composed of undifferentiated granite and gneiss of Precambrian age. The remainder consists of: (1) scattered diorite bodies of the Pochuck gabbro gneiss of Precambrian age, (b) the Stockbridge limestone of Cambrian and Ordovician age, and (c) the argillaceous and schistose beds of Ordovician age. The consolidated rocks are overlain by an irregular mantle of unconsolidated glacial deposits of outwash and till of Pleistocene age, which have an irregular distribution and thickness. In the upland areas the till generally is less than 30 feet thick but in some valleys may be as much as 200 feet thick. Outwash, consisting chiefly of sand and gravel, underlies large stream valleys. In some places the glacial deposits largely consist of silt and clay.

Water-Bearing Characteristics of the Deposits

Ground water occurs in the till, outwash, and bedrock. Records of a few wells in till indicate an average yield of about 2 gpm, which is an indication of the low permeability of these deposits. Many wells in till go dry during periods of low rainfall owing to

decline of the water table. Yields of 50 wells tapping outwash sand and gravel range from about 1 to 450 gpm and average about 30 pgm.

The yields of about 370 wells penetrating bedrock range from 0 to about 120 gpm and average about 12 gpm. Most of the wells tap granite and gneiss. There is little difference in the average yields of wells tapping the principal bedrock units.

About one-third of the total estimated pumpage of 1.5 mgd was from ground-water sources. Eleven public-supply systems use ground water wholly or in part. Ground water also is used for domestic, agricultural and some industrial purposes.

Magnitude of the Water Supply

Annually, over the 235 square miles of Putnam County there is an average precipitation of about 46 inches equivalent to about 500 mgd or 0.180 tgy. However, 24 inches, or about 0.095 tgy is available as runoff. The rest, about 22 inches, or about 0.085 tgy, is lost as evapotranspiration. These values are based on about 40 years of record, a long enough period of time so that changes of water storage in aquifers and in the soil can be neglected.

Rockland County

Rockland County contains approximately 201 square miles. The permanent population in 1950 was about 89,000 and 1955 was about 106,000. Land surface ranges in altitude from about sea level along the Hudson River in the eastern part to about 1,200 feet in the mountainous northwestern part. The eastern two-thirds of the county is a gently rolling plain which is bordered on its eastern margin by a narrow curving ridge that rises as much as 700 feet above the plain. The plain terminates against the rugged highland area of the Ramapo Mountains in the northwestern part of the county.

General Geology

Rockland County is underlain by igneous, sedimentary, and metamorphic rocks ranging in age from Precambrian to Ordovician and Triassic. The eastern two-thirds of the county is underlain by beds of conglomerate, sandstone, and shale, and associated igneous rocks of Triassic age. The sedimentary rocks are part of the Newark group. The largest differentiated unit of igneous rocks is the Palisade diabase, a sill, intruded in the eastern part of the county in Triassic time. The rocks of Triassic age dip northwesterly and terminate along a major fault marking the southeastern border of a belt of crystalline rocks of Precambrian age. The crystalline rocks consist mostly of granite and gneiss. A small

area in the northeastern part of the county is underlain by an infolded and faulted body of rocks of Cambrian and Ordovician age consisting of beds of quartzite, limestone, and phyllite. Glacial till and outwash of Pleistocene age cover the bedrock in most of the county. In some places the total thickness of these deposits is more than 300 feet.

Water-Bearing Characteristics of the Deposits

Ground water occurs in the till, outwash, and bedrock. Deposits of till are tapped by some domestic wells which generally yield less than 5 gpm. Deposits of outwash composed of sand and gravel are restricted to major valleys and yield about 55 to 1,200 gpm to individual wells. At some places the outwash is composed largely of fine-grained material which does not yield large supplies.

Most of the wells in the county tap the bedrock. The main water-bearing rocks are sandstone and shale aquifers, part of the Newark group. Yields of 220 wells tapping these rocks range from about 4 to 1,500 gpm and average about 80 gpm. The average yield of 40 public-supply wells penetrating the Newark group is about 300 gpm. The water is moderately hard. Yields of 13 wells tapping the Palisade diabase average about 11 gpm. Yields of 37 wells penetrating granite and gneiss average about 15 gpm. Yields from the other minor bedrock units are small, commonly less than 10 gpm.

Most of the water used in the county is from ground-water sources. An average of about 7 mgd was pumped in 1955, most of which was pumped for public-supply use. Some was pumped for self-supplied industrial use and the remainder was for domestic, agricultural, and other minor uses.

Magnitude of the Water Supply

The annual precipitation over Rockland County's 201 square miles is about 44 inches. This amounts to an average of about 410 mgd or 0.150 tgy. Of this about 0.072 tgy, or 21 inches, becomes runoff. Evapotranspiration accounts for approximately 23 inches of rainfall annually, or about 0.078 tgy.

Ulster County

Ulster County contains approximately 1,172 square miles. The permanent population in 1950 was 93,000 and in 1955 was 102,000. Land surface ranges in altitude from about sea level along the Hudson River to over 4,000 feet in the northwestern part of the county. The eastern half of the county is a gently rolling dissected lowland. Shawangunk Mountain and some minor ridges and valleys which trend northeasterly across the county separate the eastern lowland from the dissected plateau which forms the Catskill Mountains in the northwestern half of the county.

General Geology

The bedrock underlying Ulster County is composed of folded sedimentary rocks ranging in age from Ordovician to Devonian. The rocks in the eastern half of the county have a northeasterly and northerly strike. They mainly consist of folded beds of gray and black shale and sandstone which largely comprise the Normanskill shale of Ordovician age. Unconformably overlying the rocks of the Normanskill shale are the northwesterly dipping beds of the Shawangunk conglomerate of Silurian age. Minor ridges and valleys immediately west and north of Shawangunk Mountain are underlain by folded beds mainly of marine shale, sandstone, and limestone comprising a number of formations of Late Silurian to Middle Devonian age. The Catskill Mountains area in the northwestern half of the county is underlain by relatively horizontal beds of red and gray sandstone, shale, and conglomerate of Middle to Late Devonian age. The bedrock is overlain in most of the area by unconsolidated deposits of till and outwash of Pleistocene age. The maximum total thickness of these glacial deposits is more than 200 feet.

Water-Bearing Characteristics of the Deposits

Little is known of the water-bearing characteristics of the deposits in Ulster County because few records of wells and springs have been collected in the county to date. As in other nearby counties the main water-bearing units are outwash, till, and bedrock. Till of irregular thickness covers most of the upland areas. Average yields of wells in till probably are a few gallons per minute. Scattered outwash deposits of sand and gravel occur in major valleys and may yield as much as several hundred gallons per minute to individual wells, and where in hydraulic continuity with perennial streams their yields would not only be high but would be dependable. The bedrock is the source of water for most of the wells in the county. The yields of wells tapping bedrock units probably are on the same order of magnitude as the yields given for the same units in Orange County (p.119).

The ground water is used mostly for public supply, domestic, and agricultural purposes; a small quantity is used for industrial and other miscellaneous purposes. About 10 public-supply systems use ground-water sources wholly or in part. The combined ground-water pumpage from these systems averages somewhat less than ½ mgd.

Magnitude of the Water Supply

Precipitation on Ulster County's 1,172 square miles ranges from slightly more than 60 inches over the higher parts of Slide Mountain to 54 inches in the Overlook Mountain area; it drops off to

about 46 inches at the base of the Catskill Mountains scarp on the east and from there eastward gradually diminishes until, at the Hudson River, the amount is about 44 to 45 inches, the lowest precipitation being in the southeastern part of the county. Average precipitation over the entire county is about 48 inches, which is an average of about 2,600 mgd or 0.960 tgy. Runoff takes about 30 inches, or 0.600 tgy, and evapotranspiration losses amount to about 18 inches, or 0.360 tgy.

Westchester County

Westchester County contains a total of about 487 square miles. The permanent population in 1950 was about 626,000 and in 1955 was about 718,000. The altitude of the land surface ranges from about sea level along the Hudson River in the western part of the county, to about 700 feet in the Hudson Highlands in the northern part. Land surface consists mostly of a series of northeasterly-trending low ridges and valleys.

General Geology

Westchester County is underlain by northeasterly-trending belts of closely folded igneous and metamorphic rocks which range in age from Precambrian to Ordovician. The principal units are Precambrian: (1) Fordham gneiss, (2) Inwood limestone, and (3) Manhattan schist. In addition, relatively small areas are underlain by the Harrison diorite, Yonkers granite, infolded belts of Poughquag quartzite, of Early Cambrian age, Stockbridge limestone, and slate of Ordovician age, and miscellaneous igneous rocks such as granite, pegmatite, and undifferentiated basic intrusives. The bedrock in most of the county is covered by unconsolidated deposits of till and outwash of Pleistocene age which range in total thickness from a few feet to as much as 200 feet.

Water-Bearing Characteristics of the Deposits

Ground water occurs in the till, outwash, and bedrock. Deposits of till having a wide range in thickness are extensively distributed on the upland areas and in some valleys. The till has relatively low permeability and except where it contains large sandy lenses yields only a few gallons per minute to dug wells. Scattered sizable bodies of outwash occur in parts of the county, the largest and thickest of which are restricted to major valleys. The outwash consists mostly of sand and gravel but in places contains much silt and clay. Outwash deposits of sand and gravel yield the largest supplies in the county. Individual wells screened in these deposits range in yield from about 3 to 600 gpm. The average yield is about 200 gpm.

At least 70 percent of the existing wells in Westchester County tap the bedrock. The average yield from these wells is less than 30 gpm. Most of the bedrock wells penetrate schist and gneiss and reportedly have a range in yield from about 1 to 400 gpm. The limestone is the most productive bedrock aquifer, particularly where it occurs in lowland areas and is overlain by water-bearing deposits of outwash. Yields of individual wells penetrating limestone range up to 450 gpm. Yields from other bedrock units are relatively low.

Public-supply systems serve about 90 percent of the population. The water is pumped mostly from lakes and streams. About 21 systems use ground-water sources wholly or in part. Wells and springs also supply domestic, agricultural, and some industrial needs.

Asselstine and Grossman (1955, Part I) present detailed information on the wells and yields of wells of Westchester County.

Magnitude of Water Supply

Annually on the average, there falls on Westchester County's 487 square miles about 48 inches of precipitation. This is the equivalent of about 1,100 mgd or nearly 0.400 tgy. However, evapotranspiration losses account for approximately 22 inches, or about 0.180 tgy, thus leaving 26 inches, or about 0.220 tgy for runoff.

LONG ISLAND, NEW YORK

by Garald G. Parker

Introduction

Although not a part of the Delaware River basin, Long Island is important to this study because it is a part of the New York metropolitan area which is in the Delaware River basin service area. Although the island is surrounded by salt water, an important fact in considering the development and use of water in large quantities on the island, it contains in its huge glacial and Coastal Plain aquifers very large quantities of fresh water. These could be developed for emergency use in the New York City metropolitan area if the area were struck by severe radioactive fallout. In such an event all surface water, and perhaps some shallow ground water, would become unfit for use, but the deeper aquifers would be capable of producing supplies needed until surface sources could be decontaminated.

The Water Supply

The total volume of water stored in Long Island's aquifers is very great, probably in the order of 50 trillion (5×10^{13}) gallons. However, not all, or even very much, of the water is available for use. This is because of the delicate balance that exists between this large body of fresh water on land and the still larger body of salt water of the ocean that surrounds it on all sides. In other words, the salt-water encroachment factor is the dominant limiting factor here.

The total quantity of water available for perennial use, which has been called "safe yield", is therefore not known, although it is less than the average annual return flow to the ocean which itself is not precisely known for all the island but is estimated in table 21.

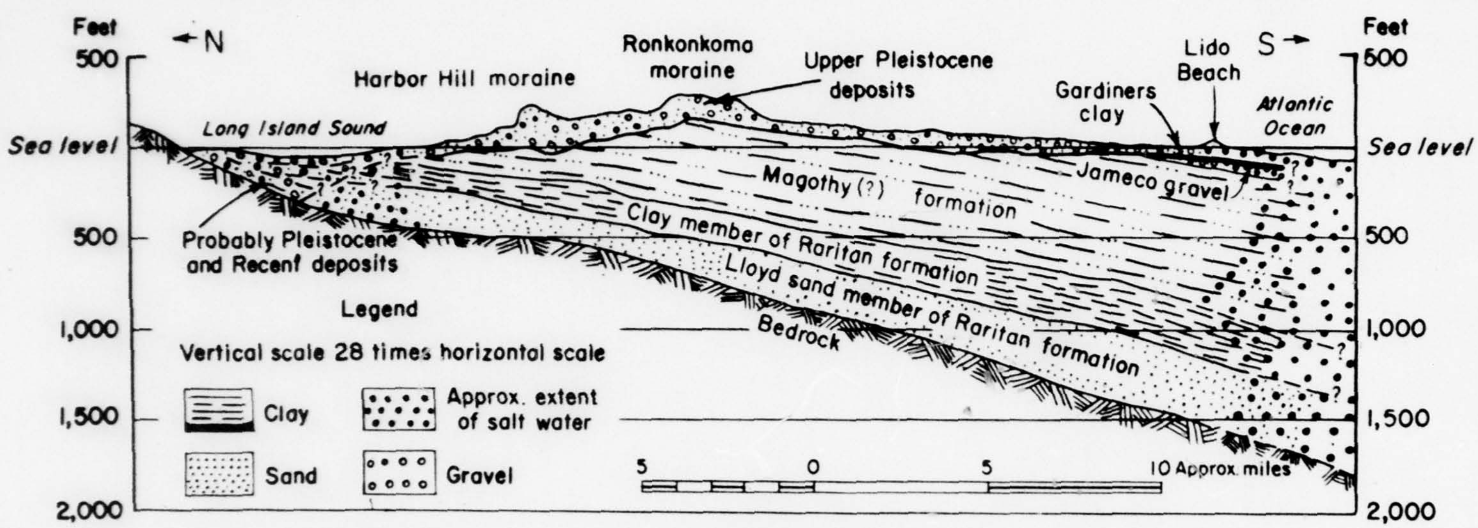
In an attempt to place the water-supply picture in proper perspective, table 21 and pl. 19 were developed. The values given are based on published data of the U. S. Weather Bureau and on both published and unpublished data of the U. S. Geological Survey, but are intended only to give the order of magnitude of the hydrologic values involved.

Of general interest is the conclusion that the values assigned to Long Island are of the same order of magnitude for other parts of the Coastal Plain covered in this report (p. 37-39). However, the water budget for Long Island (table 21) differs in one respect from that for the Coastal Plain in New Jersey and Delaware (table 4). In the water budget for Long Island, R includes unmeasured, but estimated, ground-water outflow beneath and between stream channels, as well as runoff, and is designated average annual return flow to the ocean. In the budget for the Coastal Plain in the Delaware River basin and adjacent New Jersey and Delaware, R represents only runoff; unmeasured ground-water outflow, believed to be much smaller per unit area than that in Long Island, is included in water loss in table 4.

Table 21 indicates that Long Island receives an average annual precipitation of about 2.1 mgd per square mile, which, over the 1,373 square miles of the island's surface amounts annually to approximately 2,900 mgd of new water. However, water loss amounts to about 1 mgd per square mile for a total estimated average annual loss of 1,400 mgd over the whole island. This leaves only about 1.1 mgd per square mile (1,500 mgd) of discharge from aquifers to streams and to the ocean as underground outflow.

U.S. GEOLOGICAL SURVEY

PLATE 19



A section of Nassau County is shown. (for location see pl.). There are seven stratigraphic units, only four of which readily yield water. The Gardiners clay and clay of the Raritan formation confine water under artesian pressure in the aquifers they overlie, and help keep sea water out.

WATER-BEARING FORMATIONS IN CENTRAL LONG ISLAND, N.Y.

Table 21.--Summary of water resources values, Long Island, N. Y.
(note: values are rounded to 2 significant figures and give only order of magnitude)

Average annual precipitation, P				Average annual return flow to ocean, R				Average annual evapotranspiration, Et			
mgy1/ per sq mi	tgy2/ over entire island	mgd3/ per sq mi	mgd4/ over entire island	mgy1/ per sq mi	tgy2/ over entire island	mgd3/ per sq mi	mgd4/ over entire island	mgy1/ per sq mi	tgy2/ over entire island	mgd3/ per sq mi	mgd4/ over entire island
770	1.1	2.1	2,900	390	0.56	1.1	1,500	380	0.54	1.0	1,400

Basic data:	Area	1,373 sq mi
	Precipitation (P)	45 inches average annual
	Return flow to ocean (R)	23 inches average annual
	Evapotranspiration (Et)	22 inches average annual

1/ million (1×10^6) gallons a year
2/ trillion (1×10^{12}) gallons a year
3/ million (1×10^6) gallons a day
4/ million (1×10^6) gallons a day

On Long Island there is a negligible amount of direct runoff. Nearly all the 1.1 mgd per square mile seeps into the ground, becomes ground-water recharge and then, the aquifers being full (and by nature required to remain so to maintain salt water of the ocean and sound in its "normal" position) is discharged chiefly as ground-water outflow beneath and between streams and as baseflow in streams. Thus, the streams of Long Island, none of which are large, are fed almost exclusively by ground-water discharge.

The topmost curve of pl.21 indicates the total amounts of water withdrawn from all aquifers of Long Island and projects possible 1958) quantities through 1960. It is estimated (Lusczynski, written communication) about one half of the withdrawals on the island is returned to the aquifers, therefore the other half is, in essence, consumptively used by: (1) being sewered into the ocean, (2) included in manufactured products; (3) lost by evapotranspiration; or (4) lost by other means (this consumptive use includes, of course, the water used for irrigation).

To see how important these withdrawals and consumptive uses are let us compare the pumpage for 1957 (0.137 tgy) with the total annual average return flow (0.560 tgy) and then with the total average return flow during an extremely dry year (0.365 tgy).

Thus:	0.137/0.560	approximately 24 percent (normal year)
	0.137/0.365	approximately 38 percent (probable driest year)

If, however, half the withdrawals are returned to the aquifers, the actual quantities we have to deal with are those for consumptive use.

Thus:	0.69/0.560	approximately 12 percent (normal year)
	0.69/0.365	approximately 19 percent (probable driest year)

We may conclude, therefore, that the present consumptive use on Long Island is about 12 percent of the average annual return flow and about 19 percent of the return flow during the driest year to be expected. This indicates that a great deal of additional development and use of ground water can be made. However, if lasting harm is not to be suffered from such increased development, rational plans must be developed and adopted to prevent overly large concentration of development too near the shore zones with resultant salt-water encroachment. Present studies underway by the U. S. Geological Survey in cooperation with the State, county, and city governments should lay the solid basis needed for future safe development.

Irrigation on Long Island is increasing, and total water loss is likewise increasing. Because irrigation water is largely used consumptively, about 90 to 95 percent being lost by evapotranspiration, it has an importance that most other uses of water, not being so highly consumptive, do not have.

According to the U. S. Census Bureau (1954, p. 44-49) total irrigated acreage on Long Island increased from 11,945 acres in 1949 to 37,275 acres in 1954. Inasmuch as an estimated average of 6 - 7.5 inches of water are applied during the growing season, about 1,900 mgy (6-inch rate) or 2,400 mgy (7.5-inch rate) were used in 1949, compared with 6,000 mgy and 7,600 mgy, respectively, for 1954. By counties, the irrigation water use for 1954, at 6 - 7.5-inch application rates, is distributed as follows: Kings County, 13 - 16 mgy; Queens County, 30 - 37 mgy; Nassau, 190 - 240 mgy; Suffolk County, 5,800 - 7,300 mgy.

Previously (table 21) it was estimated that the total return flow from Long Island averages about 560,000,000 mgd and during an extremely dry year amounts to about 365,000,000 mgd. Thus, maximum use of water for irrigation, compared with worst expected dry-year conditions, is 7,500 / 365,000,000, or 0.002 percent of the return flow, and can be seen to be a very minor item in the over-all water budget. However, much depends upon where and in what quantities the water is removed from the aquifers. Should it be too close to the salt-water--fresh-water contact near the shore area, salt water would be drawn in. In any case, local studies would have to be made if additional large-scale irrigation supplies were to be developed. Additional pumping would be feasible only to the extent that it would not induce serious salt-water encroachment.

Geologic Structure and Materials

Although Long Island is adjacent to rocky New England, and its bedrock is a continuation of the same rocks found on the mainland, the island is a part of the Coastal Plain rather than of the New England province. As in New Jersey and Delaware, the bedrock surface under the mantle of sedimentary rocks slopes generally seaward; on Long Island, however, the direction of the prevailing slope is more southerly than it is in New Jersey and Delaware. The dipping bedrock surface slopes from depths of only a few tens of feet below sea level in northwestern Queens County to depths of more than 2,000 feet at and beyond the south shore of Suffolk County. In central Suffolk County bedrock is about 1,400 feet below sea level. The overlying huge wedge of sedimentary rocks constitutes the ground-water reservoir of Long Island, which contains several notable aquifers.

Pleistocene Aquifers

The upper geologic layers on Long Island are of diverse Ice Age origin and are collectively called upper Pleistocene deposits . They underlie almost all of Long Island and in some places attain a thickness of about 300 feet (pl. 19). Lying stratigraphically below these deposits in the western part of the island is the Jameco gravel of early or middle Pleistocene age.

The Upper Pleistocene Aquifers

On the basis of their origin and lithology the upper Pleistocene deposits are assigned to three categories, each of which may be considered an aquifer: (1) Glacial moraines, forming two sub-parallel ridges, Harbor Hill on the north and Ronkonkoma on the south, extending almost the length of the island; (2) glacial outwash, forming a stratified sheet plain on most of the south side of the island, south of the Ronkonkoma moraine; and (3) a complex depositional sequence lying both between the Harbor Hill and Ronkonkoma moraines and also to the north of the Harbor Hill moraine.

Glacial moraines

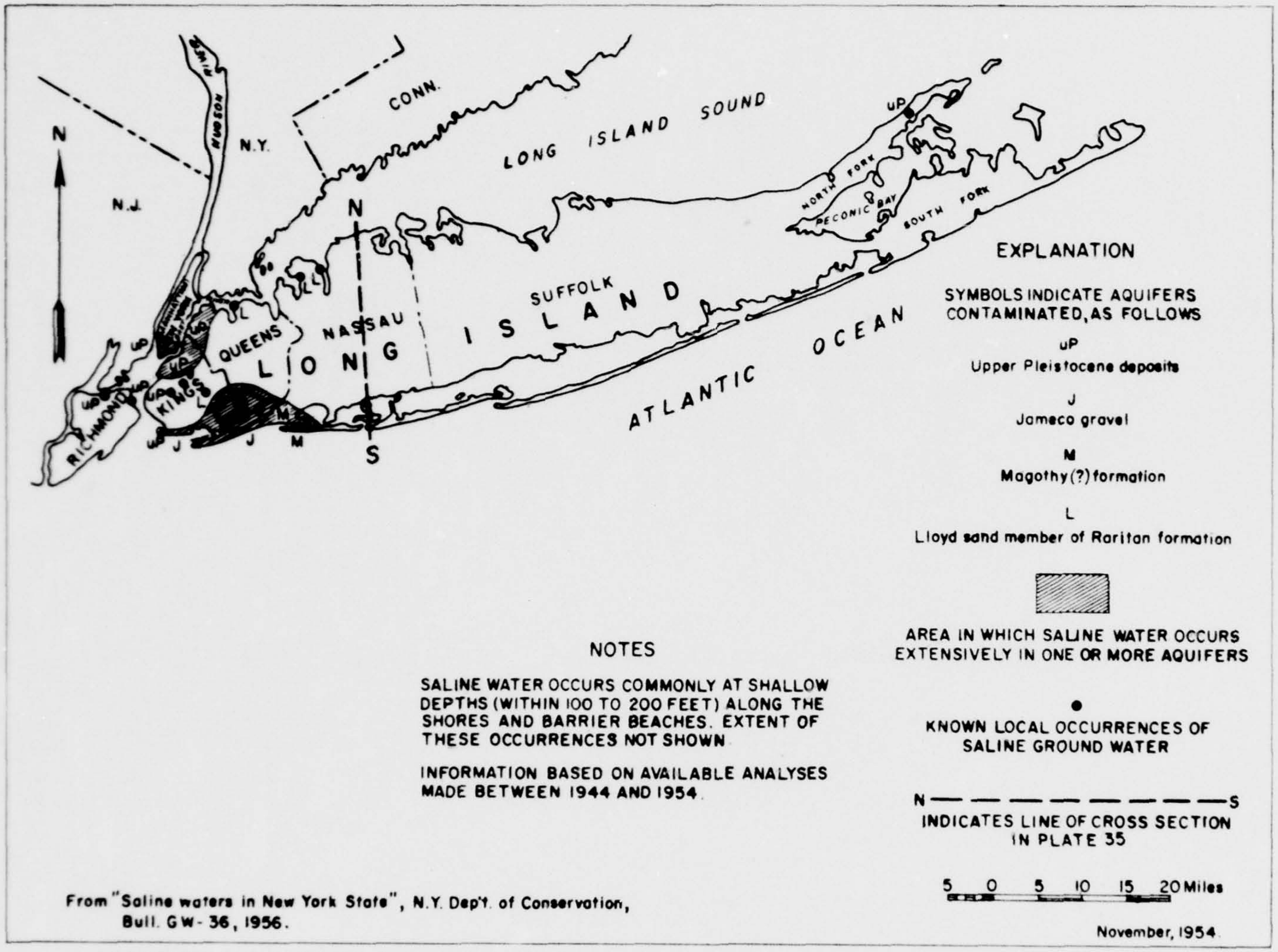
The Harbor Hill moraine extends from Kings County out along the North Fork, and the Ronkonkoma moraine extends from western Nassau County out along the South Fork (pls. 19 and 20). In their western parts the deposits of these two moraines carry local bodies of perched ground water on clayey members, but to the east there is less clay, and the gravels and sands are quite permeable and apparently allow ready movement of water through their interstices.

Glacial outwash

The outwash deposits lying between the south shore and the Ronkonkoma moraine are mostly sand and gravel and generally are very permeable. Near the shore, and beyond, there are intercalated layers or lenses of marine clay of relatively low permeability.

Glacial complex

The complex of glacial deposits in the northern part of Long Island consists mostly of stratified sand and gravel, partly of outwash origin, but there are also included two units of clayey till, one in the middle of the sequence and the other at the land surface. It will require a great deal of detailed field and laboratory study to separate those units, map them, and derive a satisfactory quantitative understanding of their hydrologic significance.



MAP SHOWING OCCURRENCES OF SALINE GROUND WATER IN LONG ISLAND, STATEN ISLAND AND MANHATTAN, N.Y.

Jameco Gravel

The Jameco gravel is the aquifer that lies stratigraphically below the upper Pleistocene aquifers. It is chiefly a body of highly permeable sand and gravel but locally includes lenses of silt and clay. The formation occurs only in Kings County, the southern part of Queens County, and the southwestern part of Nassau County. For the most part the Jameco gravel seems to fill a system of buried valleys, though in places it covers the interfluvial areas between. It ranges in thickness from a featheredge to about 150 feet and everywhere lies 80 feet or more below sea level. It was probably derived from debris carried by meltwater streams of a pre-Wisconsin glacial sheet.

Hydrology of the Pleistocene Aquifers

The Upper Pleistocene Aquifers

The upper Pleistocene deposits, which mantle the entire island, are recharged entirely by local precipitation. Lacking a connection through permeable rock with the mainland of New York and Connecticut, fresh-water cannot be transmitted from the mainland to the island naturally beneath Long Island Sound. Salt water surrounds Long Island's ground-water body on all sides. Over the years a hydrologic balance has been established by Nature between fresh water of the island and salt water of the surrounding ocean and sound. Pumping has changed this balance in some places, resulting in salt-water encroachment (pl. 20). Because most of the deposits are very permeable, direct runoff is slight.

Overlying other permeable aquifers, the upper Pleistocene aquifers serve as water-catchment and temporary storage units for the deeper aquifers. Recharge to the Jameco gravel, the Magothy(?) formation, and the Lloyd sand member of the Raritan formation passes through the upper Pleistocene deposits. The total recharge estimated to average about 1 mgd per square mile.

The upper Pleistocene ground-water body is unconfined, though in local areas it may be semiconfined, and the water table meets the sea level at the shoreline; inland the water table rises in some places to about 250 feet above sea level. Fluctuation of the water table chiefly reflects changes in rate of recharge from precipitation; however, in those areas where pumping is heavy water-table fluctuations may be more the result of changes in rate of pumping than of changes in rate of precipitation.

In those areas on western Long Island where perched bodies of water occur in the upper Pleistocene deposits, more than one "water table" may be encountered in drilling wells.

Because of their bulk and permeability, the upper Pleistocene deposits comprise the most productive aquifer system on the island, probably now producing about half the gross pumpage, or nearly 0.061 tgy in 1955. Plate 21 which shows estimated gross withdrawals from aquifers on Long Island, and estimated consumptive use therefrom, gives an overall view of estimated withdrawals from 1950 to now, and projects use to 1960. This graph indicates that in 1957 the gross withdrawal from the upper Pleistocene aquifers amounted to about 0.068 tgy. If pumping should continue to increase at its present rate, we should expect withdrawals from these aquifers to reach about 0.081 tgy in 1960.

Jameco Gravel

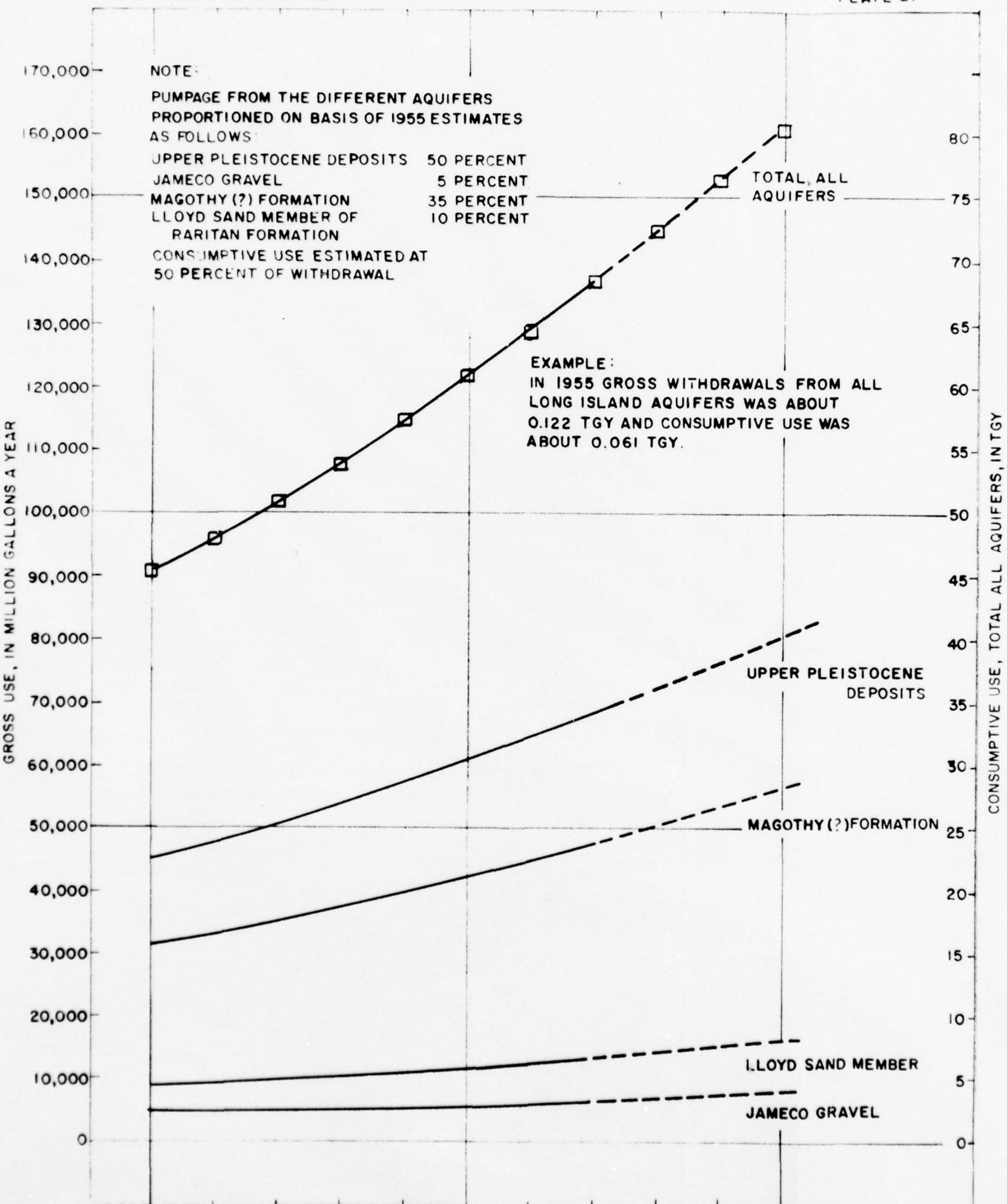
The Jameco gravel was once an important source of water in Kings County, but salt-water encroachment in the aquifer, induced by fairly large-scale pumping, has caused abandonment of all public supplies formerly obtained from it (Lusczynski, 1952). The Jameco gravel still supplies substantial quantities of water in Queens County and in southwestern Nassau County. It probably yields on the order of 5 percent of the gross pumpage on the island, or about 0.006 tgy in 1955(pl. 21).

Water in the Jameco gravel occurs under artesian or semiartesian conditions, being confined in varying degrees by the overlying Gardiners clay, which separates the upper Pleistocene aquifers from the Jameco gravel. Locally the clay forms a leaky aquiclude but at most places it is a fairly effective barrier to water movement across its thickness of 10 to 150 feet. Some of the recharge occurs to the Jameco gravel through the more leaky and permeable parts of the Gardiners clay; the remainder of the recharge enters the Jameco where the Gardiners clay does not extend above it.

Cretaceous Aquifers

Magothy(?) Formation

The Magothy(?) formation in Long Island, like the similar and presumably correlative formation in New Jersey, Delaware, and Maryland, is a wedge-shaped deposit of nonmarine Cretaceous sediments having its thick segment seaward (pl. 19). In Kings, Queens, and Nassau Counties the Magothy(?) formation is overlain by the upper Pleistocene deposits, except in the southern parts of those counties where it is overlain by the Gardiners clay extending beyond the



GRAPH SHOWING PUMPAGE AND CONSUMPTIVE USE FROM AQUIFERS OF LONG ISLAND, N.Y., 1950-1957, PROJECTED TO 1960

Jameco gravel. The Magothy(?) formation is present under most of Long Island, being missing only in the western and northwestern parts of Kings and Queens Counties.

The Magothy(?) formation in Long Island is a complex, heterogeneous assemblage of lenses and stringers of clay, silty clay, silt, fine and coarse sand, and some gravel. Generally these deposits seem to be distributed unsystematically except, perhaps, in the western end of the island where the lowest few tens of feet of the formation appear to be more gravelly and sandy, and thus more permeable, as a whole, than the rest of the formation.

The upper surface of the Magothy(?) has been eroded to a relief of several hundred feet; its maximum elevation is about 220 feet above sea level in southern Queens County. The base of the formation is fairly uniform, lying nearly parallel to the deeper bedrock surface. Thus, the formation has a range in thickness from a featheredge to at least 700 feet.

Lloyd Sand Member of the Raritan Formation

The Lloyd sand member of the Raritan formation is the deepest aquifer on Long Island. Nowhere does it crop out at the land surface, but it underlies practically all the island and extends outward beneath Long Island Sound and the Atlantic Ocean for unknown distances.

The Lloyd member consists mostly of sand and fine gravel, with lenses of clay, sandy clay, and fine sand. The lenses of sand and gravel seem to occur prominently in several permeable zones separated by less permeable zones consisting chiefly of clay and silt.

The Lloyd sand slopes southeastward nearly parallel to the subjacent bedrock surface, dipping from about 100 feet below sea level in northern Queens and Nassau Counties to about 1,400 feet below sea level in southeastern Nassau and to about 1,700 feet below sea level in Suffolk County. The thickness increases somewhat to the southeast but in most places is about 250 feet.

Overlying the Lloyd sand member almost everywhere is the clay member of the Raritan formation. The clay member consists of clay, silty clay, and some included lenses of silty sand and sand, which collectively constitute an aquiclude.

Hydrology of the Cretaceous Aquifers

Magothy(?) Formation

The Magothy(?) formation which is presumably correlative in part with the Magothy formation in New Jersey, Delaware, and Maryland, is recharged by ground-water seepage from the overlying permeable deposits, chiefly the upper Pleistocene aquifers and the Jameco gravel. Ground water in the Magothy(?) is generally confined, less in the upper parts of the formation in the central part of the island, and more in the deeper parts of the formation where the confining effects of the beds of low permeability are felt. Along the southern shore of Long Island most wells penetrating the Magothy(?) flow under natural artesian pressure. In southwestern Nassau County artesian heads up to 5 feet above mean sea level are not uncommon; the head increases to the east and reaches 9 feet within a few miles of the Suffolk County line. The artesian head probably continues to increase farther east along the shore to a maximum somewhere in Suffolk County, beyond which it decreases.

Fluctuations of the piezometric surface of the Magothy(?) formation are primarily those caused by pumping, in contrast to the water-table fluctuations of the upper Pleistocene aquifers which reflect the effects of precipitation. Withdrawal of water from the Magothy(?) formation is limited by the capacity of its geologic materials to receive water from the areas of recharge and to transmit it to the points of withdrawal.

The salt-water--fresh-water relationships in the Magothy(?) formation are now being explored. Although they are not completely understood, it is believed that, in general, hydraulic continuity exists between the landward portion of the aquifer and its extension under the ocean. The lower part of the Magothy(?) at Atlantic Beach, near the west end of the South Shore barrier beach, contains water with more than 1,600 ppm of chloride. Farther east the water is fresh, where the artesian head is sufficient to prevent the landward movement of salt water in the Magothy(?). Little is known at present of the Magothy(?) along the north shore; however, a field study is in progress.

The Magothy(?) formation is the largest aquifer on Long Island and the second most important source of water; the upper Pleistocene aquifer, though smaller in total area, ranks first. In 1955 the Magothy(?) produced about 35 percent of the gross pumpage on the island, or about 0.043 tgy (pl. 21).

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Cretaceous Aquifers

Magothy(?) Formation

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Lloyd Sand Member

The Lloyd sand member, fourth and lowermost of the principal aquifers of Long Island, is capped by the clay member; hence, water in the aquifer occurs under artesian conditions. In the central part of the island the flow is downward from the overlying formations to the Lloyd. Thus, recharge can be effected by slow and devious percolation through and around the lenses of clay and silt, or possibly through erosional gaps in the clay layer (De Laguna and Perlmutter, 1949).

Near the shores the water movement is upward from the Lloyd sand member to the overlying material, and wells drilled in the shore area will flow because of artesian pressure. In some areas, as near the western end of the barrier beach, fresh water may be obtained from the Lloyd, whereas overlying beds contain only salt water. Along the north shore, reportedly one or two wells drilled years ago into the Lloyd encountered only salty water.

The Lloyd member is not greatly used, yielding perhaps about 10 percent of the gross pumpage on the island; presumably it could sustain additional fairly large development away from the shores. A glance at the graph, plate 21 indicates that the Lloyd, in 1955, produced about 0.012 tgy and that it will produce about 0.016 tgy in 1960, if the present rate of increase continues.

AQUIFER-MANAGEMENT PRACTICES

Aquifer management includes all those practices that are designed to enable man to make the maximum permanent use of the natural underground reservoirs. The hydrologic characteristics and the present uses being made of the aquifers in the Delaware River service area have been described earlier. The purpose of this section is to discuss some of the aquifer-management practices that are of value in increasing and protecting the ground-water supply. Let us first consider the matter of wells, their development and operation; items largely paraphrased or quoted directly from W. C. Rasmussen (written communication, 1957).

WELL AND WELL-FIELD DESIGN, DEVELOPMENT, AND OPERATION

Great advances have been made in the last 30 years in the design and construction of water wells. These advances include: (1) The use of a wide variety of types of well casing; (2) a multiplicity of screen types from which to choose for use in specific cases; (3) the methods of determining the kind of screen to use; (4) the method of mechanical underreaming and gravel packing; (5) the processes of chemical and physical treatment of screens, casings, and even of the aquifer materials adjacent to the well screen to increase well yield; (6) the hydraulics of determining proper spacing of wells and the influence that a pumping well will have on other wells; (7) greatly improved pumps to meet diverse needs; and (8) the use of horizontal collector-type wells in areas of induced recharge.

The scientific and economic design of wells or of well fields to capture the optimum amount of water is the responsibility of ground-water consultants and other specialists outside the U. S. Geological Survey. It is appropriate here only to sketch selected aspects of optimum well-field design. Let us first consider well spacing.

Well Spacing

Spacing of most water wells has been a happenstance process. Location of the first well in an area has often been dictated by convenience to other facilities or by limitations imposed by land ownership. Frequently, when a well field is developed, wells are placed in line, with direction and separation dictated by the geometry of the area available. Little thought, in general, has been given to whether the aquifer being developed is artesian or water-table, or to such hydrologic factors as: (1) The geometry of the

aquifer; (2) the direction of ground-water flow; or (3) induced recharge. In fact, most of these elements of the hydrology of well-field development were unknown and unappreciated a generation or two ago in most parts of the country; and in the Delaware River service area even now knowledge of these factors is generally lacking.

Today the problem of proper spacing of wells can be approached scientifically if the aquifer constants (such as the coefficients of transmissibility and storage), the geometry of the aquifer, its relation to other aquifers and aquicludes, and other physical and economic factors are known. All too frequently, however, data needed for the best design of a well field are not available, possibly because of a lack of awareness of the specific data required and their proper utilization. Developers of ground-water supplies may find some useful parallels in the petroleum industry, where the unit operation of many large oil fields, which requires rational spacing of wells, has been in practice for more than 20 years. Competitors have cooperated willingly with the result that more oil is recovered at lower cost than could have been recovered by haphazard development.

The formulas necessary to solve many reservoir problems have been defined (Muskat, 1937) on the assumption that the basic coefficients and geometry of the reservoir can be determined. Data have not yet accumulated in sufficient detail in any except localized parts of the Delaware River basin to permit applying, on an areal basis, hydraulic theory to a rational plan for spacing wells in the several aquifers. Until such large-scale regional planning and coordination become necessary, however, there is opportunity for steady improvement in the design of individual multiple-well systems. But the success of a battery of wells is largely based upon the successful development of each individual well. Let us next consider this important matter.

Well Development

Well development is concerned with obtaining an adequate, assured supply of potable, clear water. This is done by means of mechanically, hydraulically, or chemically treating the well before it is placed in service. Modern development frequently takes as long as, and sometimes several times longer than, the time required to drill, case, and screen the well.

Development might be considered to start with the choice of the best aquifer, after a test hole or pre-existing information has revealed one or more water-bearing sands. Decisions must be made to

case off those parts of the aquifer that are too fine-grained or are polluted, if the development is to be successful. On expensive wells, these decisions should be made on the basis of: (1) Study of cuttings or cores; (2) electrical logging; and (3) bacteriological (in some cases) and chemical examination of water from succeeding depths. This is best accomplished by an experienced ground-water geologist working with the driller. On less costly wells the driller will frequently make the decision, using his drilling log and sample cuttings as guides. In order to develop the desired well yield, in areas of thin or silty sand strata, it may be necessary to use multiple screens with blank sections of casing opposite fine-grained layers. These can be quite accurately located by careful electric logging: in fact, these changes in lithology are often more accurately determined by interpretation of an electric log by a competent geologist than by examination of the most carefully taken well samples.

The screen is one of the most important components of a properly designed well. Choice of the correct slot size is critical, inasmuch as a certain percentage of fine material must be denied passage into the well while the maximum rate of passage of water is encouraged. Commonly a slot size is chosen that will allow a certain percentage of the smaller sand grains to pass into the well and be pumped to waste. Gradually an envelope of coarser material is developed around the well, and the water clears. This method is called "natural" development.

The expensiveness of good screens often influences the decision on how much screen to set, even though hydraulically it may be advisable to screen as much of the aquifer as possible. Exact positioning and placing of a screen is necessary, if development time is to be held to a minimum. A screen set only 1 or 2 feet out of proper position may allow fine sediments to enter the well continuously, and the water may never clear. As mentioned above, electrical logging has been found more reliable than other logging methods to locate formation boundaries and permit casing and screening with the necessary precision.

Gravel packing is common today in many wells designed for high yield. Even when a well is to be gravel packed, the choice of screen slot is important, because the texture of the aquifer determines the proper size of the gravel, and the size of the gravel in turn determines the proper slot size of the screen.

The method of development--whether by surging, overpumping, blowing with air, use of dry ice, backwashing, or bailing--may affect the ultimate yield and longevity of the well. The use of acid, in limy sand like the Vincentown sand, is sometimes helpful.

The use of polyphosphate detergents may be helpful in wells developed in slightly clayey or irony formations. The new method of pressure-fracturing is being used in consolidated formations, but is not applicable to unconsolidated materials. Also, with careful application of the method, use of explosives in some consolidated rock formations is a successful means of fracturing the rocks to open additional channels for flow of water to the well.

The length of development period is important to insure that the well will not yield undue amounts of sand, silt, or other sediment after it is placed in service. An 8-hour development period may be adequate for wells of small or moderate yield in unconsolidated aquifers, whereas a day or several days may be required for a high-yield well in the same formation; in most consolidated rocks shorter periods of time are generally required for development of wells (after drilling is complete) than for unconsolidated materials.

Bennison (1947, p. 219-251) has given an excellent discussion of the problems of developing water wells. It is important to recognize, however, that even the best drillers, using the most modern equipment and techniques, and allowing adequate development time, are occasionally unable to develop the quantity or clarity of water desired. For example, successful development of wells in the Magothy and Raritan formations in northern Delaware has been particularly difficult. Competent drillers in this area have spent a month, or even more, trying to develop wells in parts of these formations and have failed to obtain well yields greater than 75 gpm of "milky" water. Experience in northern Delaware has shown that many strata which indicate high self-potential and high resistivity on the electric log, and which yield medium- to coarse-grained sand in washed samples from the rotary-drilling mud (generally considered indications of permeable sands), are so silty that long development and low yield are typical. Only by coring these sands would the developer be warned of impending failure. That the foregoing experience has been costly is attested by the records of several drillers indicating as much as $30,000 for a "dry hole".

Well Maintenance

After a well is in service, it usually requires periodic maintenance. Not only do the turbines and shafts of the pumping equipment wear out, but the well casing may deteriorate, screens may become corroded or encrusted, or both, and the aquifer itself may become plugged in the vicinity of the well. The maintenance problems are significant because they determine, in part, the extent to which drillers and water users will attempt development of an aquifer.

The quality of water is particularly significant in some well-screen and aquifer-development problems. Evidence of gradual plugging may not be recognizable on the basis of well yield alone, because maintenance and operating personnel may increase the pump speed or the number of pump stages, or may lower the bowls of the pump, to obtain the same yield at greater drawdown. A clue to possible decline in the over-all efficiency of the development may be found in the specific capacity of the well (yield, in gallons per minute, divided by drawdown of water level in the well, in feet), which gradually declines as plugging occurs.

In some places water-supply developments in the Quaternary deposits of this area have been difficult to maintain, owing to blocking of the pores of the formations close to the well with flocculent iron and clay. The remedial treatment, requiring from a day to a week has involved back-flushing with a polyphosphate detergent. Some firms drill enough wells so that one can be out of service and under treatment while the others remain in operation. This, of course, adds to operational costs but where it can be anticipated and planned, it becomes routine.

Well maintenance may include mechanical treatment, such as the removal and scrubbing, or replacement, of screens; or acidizing which, although somewhat corrosive of casing and screens, may open the formation and prolong the life of the well.

Few data have been accumulated on long-term performance characteristics, longevity, and "mortality" of wells, yet these factors are important and are, in large part, geologic or chemical problems.

Much remains to be learned about well maintenance. Possibly the minor extent to which the Vincentown sand is developed is related to maintenance problems. In years to come, superior maintenance methods should extend the usability of wells and aquifers.

PROTECTIVE BARRIERS

Prevention of the encroachment of contaminated or polluted waters has become the subject of much investigation, as revealed by an extensive bibliography, annotated by Todd (1952). The methods involve the building of protective barriers in the intake area, between the undesirable water and the good water. Among the methods in practice, chiefly in the West are: (1) Waterproofing the sides and bottom om a canal or stream containing bad water; (2) digging a trench to impermeable clay and backfilling it with impermeable material; (3) pumping a setting-type emulsion through input wells, to develop an

impermeable screen: (4) grouting in permeable limestone or fissured rocks; and (5) pumping fresh water down a line of wells along the edge of the encroaching body of water of poor quality to create a retaining fresh-water head.

So far as the writers know, none of these methods has been tried in the areas of contamination in the Delaware River basin. All of them are expensive, and until occasion warrants, probably none will be tried.

The use of outpost wells to detect the encroaching of undesirable water is a recommended procedure. Three such wells have been put into service by the Corps of Engineers along the Chesapeake and Delaware Canal (Rasmussen and Beamer, 1956). The intake area of the Magothy formation and the Raritan formation is crossed by the canal just west of the boundary of the Delaware River basin. Two wells are emplaced in the Raritan formation and one in the Magothy formation, for periodic sampling and measurement of water level. No contamination was recorded during the first year of measurement.

RETENTION OF RUNOFF

In some areas of lowered ground-water level, it may be desirable to retain runoff, to permit maximum infiltration opportunity. Ditches and canals can be used to distribute the runoff across aquifer intake areas; and check dams, described in a later section (p.143) will aid in artificial-recharge practices.

DRAINAGE

A need more pressing than the retention of runoff in many rural parts of the Coastal Plain of the Delaware River basin is the drainage of waterlogged lands. This is particularly true in the southern part of the Coastal Plain area. By lowering the water table 1 or 2 feet some water that would have been evaporated or transpired can be converted to runoff. Water conservation would require bringing the outflowing water to beneficial use, and at present, this is not practical in most places.

DISPOSAL OF UNDESIRABLE EFFLUENTS

All too commonly, the undesirable effluents of industries or municipalities have been discarded untreated, on the ground, in "disposal" wells, or in streams, although the State boards of water-pollution control are gradually abating this practice. But large tidal streams, like the lower Delaware and Christina Rivers, are almost open industrial sewers for wastes that are untreated and perhaps considered untreatable. Possibilities of effecting water-resources development, outlined in the section on tidal area controls suggest a partial answer to this problem in an industrial drainage canal, developed on an aquiclude, to carry the undesirable effluents farther down the estuary.

ARTIFICIAL RECHARGE

Artificial recharge has been practiced successfully in many areas, but usually where water is at a premium and the cost is justified, as in parts of the western United States. Barksdale and DeBuchananne (1946) have described the artificial recharge of productive aquifers in New Jersey, outside the Delaware River basin. It may be many years before artificial-recharge practices are widely needed or adopted, but there are places in the Delaware River basin where deep cones of depression in the piezometric surfaces warrant early consideration of recharge by artificial means. The cones of depression developed in the piezometric surfaces of the Magothy and Raritan formations in the Philadelphia-Camden area are one example; in Delaware the Patuxent formation in the Delaware City area, the Cheswold aquifer in the Dover area, and the Frederica aquifer in the Milford area, are other examples.

The means for accomplishing artificial recharge require a dependable water source and either input wells, check dams, infiltration canals, or spreading basins, according to local geology and economics.

Input Wells

The use of input wells, usually to restore cooling water to a formation, is the most common method of artificial recharge in the East. On Long Island, input wells are required for each air-conditioning well supplying more than 100,000 gpd. The water circulates in an airtight system and is returned to the ground unaltered except for a slight rise in temperature.

At Louisville, Ky., it was found that the ground-water level was declining at an alarming rate because of greatly expanded use of ground-water supplies to operate industrial plants during World War II. Quantitative studies of the aquifer indicated that the pumpage was about 20 mgd more than the recharge. Industries voluntarily effected many economies of water use, and at two plants cold surface water was artificially recharged into the aquifer during the winter, then pumped out again in the summer when the surface water was too warm. Through knowledge of the industrial needs, the hydrology and geology of the aquifer, and teamwork among the users, the Louisville problem was solved and the total withdrawal from the aquifer is now adjusted to the recharge. Such practices may become fairly common in the Delaware River basin in the future.

Input wells generally must be supplied with nonturbid and chemically stable water to prevent plugging. This and many related problems of recharging aquifers through input wells, using surface water, is now undergoing research by the Geological Survey and other agencies in several places, notably in Arkansas, Texas, and California.

Check Dams and Spreading Basins

Perhaps one of the most practical means of artificial recharge is to build a low dam on each surface stream just below the outcrop or intake area of each aquifer so as to raise the head of the water in the aquifer and induce more water to move down the dip beneath the confining beds. Artificial recharge can be accomplished also by constructing spreading basins. These usually are shallow ponds or pits that receive excess runoff during storms. The stored water is allowed to seep into the underlying aquifer for later withdrawal. The basin bottom must be maintained in a permeable condition, and either a considerable hydraulic gradient or a zone of aeration must be maintained between the water in the spreading basin and the water in the formation. At any given place, the percolation rate will be greatest when the water table is well below the bottom of the recharge basin. Under these conditions percolation is vertically downward and proceeds at a maximum rate. The depth to the water table does not affect the rate of percolation, however.

For more than 50 years Runyon pond at the Perth Amboy Water Works, about 26 miles northeast of the Delaware River basin, has been used effectively as a spreading basin to recharge the Old Bridge sand member of the Raritan formation at a rate of 0.6 mgd per acre (Barksdale and DeBuchananne, 1946, p. 727); and such recharge basins are currently being used successfully on Long Island to receive the drainage from storm-water conduits.

Infiltration Canals

Infiltration canals developed over permeable substrata offer a means of inducing waters, which otherwise would have gone to waste as flood runoff, to seep into, and be stored in, aquifers for later use. Such canals cost no more to construct than other canals or ditches of similar size, but because they tend to silt up they cost more to maintain. As an example of a situation where an infiltration canal might successfully be used as a factor in aquifer management.

Sprinkling Systems

For several years, on farms at Seabrook, N. J., recharge has been applied by sprinkling. The water applied is waste water from a vegetable-processing plant. Barksdale and Remson (1956, p. 522) observe:

"On the other hand, at Seabrook, N. J., where recharge water is applied by sprinkling, no soil management has been necessary. The organic matter in the water is removed by biochemical action in the soil. The accelerated soil-forming processes and plant growth that accompany the irrigation seem to maintain and may even increase the infiltration capacity of the forest floor. Some parts of the Seabrook waste-water spre ing area have received 4,000 inches of water during the last 4 years and have suffered no apparent diminution of infiltration capacity. Gradual changes in soil structure over a longer period may produce adverse effects, but present indications suggest improvement rather than deterioration of the infiltration capacity". Such a high rate of infiltration is possible only where the aquifer is very permeable.

INDUCED RECHARGE

Induced recharge may be thought of as water seeping from streams, lakes or swamps, into aquifers as a result of the cone of depression around a pumping well or a well field spreading far enough to intersect a body of surface water. In a sense it is a form of artificial recharge.

In the early development of wells in this area, induced recharge was accidently begun. Now, it is possible to take advantage of our knowledge of the geologic and hydrologic factors concerned and either intentionally induce or prevent recharge from the stream--a form of conservation of water supply and a definite factor in aquifer management.

Where drawdown in a well reverses the gradient from river to well, gradients very much steeper than exist in nature may become established, and under these circumstances much larger quantities of water will move from the river into the aquifer than previously moved from aquifer to river. Barksdale, Greenman, Lang, and others (1958, p. 104-108) discuss this situation in considerable detail and most of the following discussion is condensed from their report.

The potential induced recharge, where an aquifer is in direct contact with the river, is directly proportional to the permeability and thickness of the aquifer and to the hydraulic gradient established in it by pumping. This potential, however, will be decreased by river-bottom mud, silt, or clay, or by limited area of contact between the river and aquifer. If, for example, sands and gravels of an average aquifer in the Raritan formation of the Camden-Philadelphia area are directly exposed to river water, a strip about 100 feet wide would accept as much water as the aquifer could transmit. On the other hand, where the aquifer in the river bottom is covered by clay, induced recharge would be negligible, for 1 foot of clay creates as much head loss as 10,000 feet of aquifer material at any given rate of flow.

The desirability of inducing recharge from a stream is dependent on the quality of the stream water as well as the quantity available. Induced recharge by water from the Delaware River below Marcus Hook, Pa., under prevailing quality-of-water conditions, would generally be undesirable because of the probability of contaminating large areas of the aquifer with water of poor quality.

There is substantial evidence that induced recharge from the Delaware River is already occurring in the Philadelphia-Camden area. An aquifer test on the Morro Phillips tract in Camden indicated that after 2 years of operation on a new well near the river would be delivering about 90 percent river water.

It is evident that the relationship of water in the lower Delaware River to the aquifers in hydraulic contact with it must be carefully considered in the future development of these aquifers or of dredging and deepening of the river.

AQUIFER STORAGE AND INDUCED RECHARGE

In the hard-rock region there are in some places thick, extensive, and permeable glacial deposits, chiefly in some of the larger river valleys (pls. 14 and 15). Where connected hydraulically with a permanent body of water, such as a large lake or a perennial stream, these bodies, largely of sand and gravel, offer tremendous water-supply potential. Large supplies, 900 gpm from an individual well is reported, have been developed for perennial use in these aquifers. However, by temporarily pumping from the aquifers at a rate greater than the recharge rate, storage space can be created in which part of the streamflow can be stored, thus preventing some wastage of the potential water crop by runoff to the sea.

Manipulation of aquifer storage does not, of course, increase the total water supply in the basin, unless by lowering the water table evapotranspiration from the aquifer is reduced; the total water-supply potential is determined by the relationship that exists between precipitation, runoff, and water loss. However, such manipulation conserves water, makes more water locally available over a longer period of the year, and thus may be highly important. Also such factors as lower temperature and relative freedom from contamination may make ground water more desirable than river water.

As an example, let us consider the Delaware River valley between Port Jervis, N. Y., and Milford, Pa. Here the valley is filled with glacial outwash and some till consisting of sand, gravel, silt, and clay to an average depth of about 100 feet over a width of about a mile; the length of this stretch of valley fill is about 6 miles--the distance between Port Jervis and Milford--but the valley fill extends both northeast and southwest. In this mass of material between Port Jervis and Milford, assuming that the specific yield is about 15 percent (perhaps conservative) there would be about 18,000 million gallons of water in storage. Now suppose, by proper spacing and pumping of wells, that one-fourth of this stored water could be withdrawn from the aquifer except for a strip 1,000 feet wide beneath the river. Under these assumed conditions, there would be produced from storage alone, about 3,600 million gallons or enough to supply 200,000 people for 3 months at 200 gpcd. However, while this much water was being withdrawn from storage in the aquifer, which is connected hydraulically with the river, a somewhat greater amount would seep from the river, and to a minor extent from the adjacent rocks of the valley walls and floor, as induced recharge brought about by pumping of the wells. Moreover, when one-fourth of the deposits on both sides of the river became dewatered, the rate of induced recharge, chiefly from the river, would be an estimated 100-150 mgd.

How might this affect low flows of the river? The minimum low flow in this stretch of the river, after completion of the Cannonsville dam (scheduled for 1960), as set by the U. S. Supreme Court decree, with respect to New York City diversions, is 1,750 cfs (1,130 mgd) at Montague, N. J. If these operations induced as much as 150 mgd to seep from the river at a time of minimum flow, the daily flow of the river would be reduced by about 13 percent. Clearly this would not be in keeping with provisions of the U. S. Supreme Court's decree.

Probably no one would argue that such water legally could be withdrawn and consumptively used, either within or without the basin; however, it seems likely that the argument would be advanced that within-basin uses--largely non-consumptive as for municipal or industrial uses or both--might be legally made. If such pumping were done, legal suits might develop over the water rights involved, and, as this is an interstate aquifer and stream, the rights of citizens in New Jersey and Pennsylvania, and perhaps New York also, might be affected.

Earlier potential ground-water developments were discussed involving aquifers of the Coastal Plain and it was indicated that legal difficulties may well be expected from these developments. These situations are not untypical of the sort of water-law suits that may eventually be settled by court decree if State laws and (or) interstate compacts governing such situations are not developed in time.

In the example for the aquifer between Port Jervis, N. Y., and Milford, Pa., we have illustrated what might be done in terms of upriver ground-water storage enlargement in only one short segment of the river valley. There are numerous other places where similar successful efforts might be made, although there are not many places in the basin outside of the Delaware River-Neversink River-Basher Kill trough where the permeable glacial outwash and Recent alluvial deposits are so deep and extensive (pl. 14). Nonetheless, there are numerous smaller strips of these permeable deposits in the basin; all told they offer tremendous potential opportunity for additional water development, especially for local industries and municipalities. However, before any large-scale developments of these upbasin aquifers are attempted, specific hydrologic investigations of the sites under consideration must be made by competent hydrologists.

POSSIBILITIES FOR FUTURE GROUND-WATER DEVELOPMENT

The greatest potential for development of uncommitted ground-water supplies exists in the Coastal Plain, especially in the Cohansey sand and, to a lesser extent, in the nonmarine Cretaceous sediments, in the Quaternary deposits, and in the Kirkwood formation. The total present (1956-57) use, about 210 mgd, is only an estimated one-eighth of potentially available ground-water supplies, about 1,600 mgd, in the lower part of the basin. The remaining seven-eighths of the potential ground-water supply, or about 1,400 mgd, in the Coastal Plain of the basin, offers the greatest opportunity for future expansion of water supply below the Fall Line.

However, because of the many difficulties involved, it is considered impractical to develop more than an estimated half of the potential annual ground-water supply. In other words, for the area considered above, maximum practical development, without recourse to artificial or induced recharge, may be on the order of 800 mgd. But to achieve this there would have to be either an adequate dispersal of water works, industry, and population, or the transportation of water by pipelines, to areas of water need. In the ultimate development of the ground-water potential of this area extensive aqueducts may become commonplace.

The above estimates are based on long-term averages of precipitation, runoff, and evapotranspiration. Periods of several years of subnormal precipitation would cause marked reductions in the water available from well fields developed in shallow aquifers of low storage potential but would have little effect on the total available ground water in the area. The values shown are useful only in an appraisal of the total ground-water resources of the area--not for specific site developments.

To achieve the maximum development of the ground-water resources of the Coastal Plain many difficulties will have to be overcome. For example, planned controls would be needed to insure proper spacing, development, and pumping of wells. A program of education in the reasons for the necessity of such controls might be required to induce the land owners to accept them. Also, even if pumping could be properly executed to capture most of the potential ground-water supply, there is always the possible danger of salt-water encroachment, or of pollution and contamination of the aquifers by the disposal of wastes from habitations, industrial plants, and cities. Nonetheless, these Coastal Plain aquifers offer tremendous possibilities for future water supplies, and in the course of time, with or without planning, more and more wells will be installed and water taken from them. New Jersey

is fortunate, indeed, to be able to pursue its present policy of purchasing and developing for future water-supply reserves large acreages of land not now in great demand for private ownership and use.

In the Appalachian Highlands (hard-rock) part of the basin and especially in the area containing glacial deposits, large additional ground-water developments can be made. These opportunities are most favorable wherever fairly sizable permeable deposits of gravel and sand are hydraulically connected with perennial bodies of surface water. Scores of isolated patches of thick glacial outwash thus favorably situated for high rates of recharge exist in most of the large stream valleys in the glaciated part of the basin (pls. 14 and 15).

Although the average annual ground-water recharge to, and discharge from, the consolidated-rock aquifers of the Appalachian Highlands is very large, only a very small fraction of this amount can be recovered for use owing to the low permeability and small storage capacity of the aquifers. Instead, development of surface-water supplies, which of course includes base flow of streams (largely ground-water discharge), will continue to be dominant in the Highlands; large ground-water supplies will be developed only locally, as in the glacial outwash deposits along major streams in the glaciated part of the area.

In the Coastal Plain of New Jersey and Delaware, future water developments of large scale quite likely will take advantage of the aquifer-stream relationships to develop the maximum water yield from a given area. By inducing recharge or by artificially recharging aquifers, total yields may be increased considerably. As an example of an area now (1957) under investigation for such development, let us consider potential development of water in the Pine Barrens of New Jersey.

The Pine Barrens form a huge tract of more than 2,000 square miles in the central part of the Coastal Plain of New Jersey (pl. 3). They were originally called "barren" because it was difficult to grow corn on the relatively infertile, sandy soil. The Barrens coincide generally with the outcrop of the Cohansey sand or the overlying Quaternary deposits. Pines, oaks, and shrubs (dwarfed over large areas of the Barrens), with tufted grass, are typical of the natural vegetation. More than 300 square miles of the Pine Barrens are in the Delaware River basin, chiefly in parts of Burlington, Gloucester, Salem, Cumberland, and Cape May Counties.

In 1876 Joseph Wharton bought a large tract in the Pine Barrens, and in 1878 began buying large additional acreage with the intention of using it for the future water supply of Philadelphia. This plan

was nullified when the New Jersey State Legislature forbade the removal of New Jersey water to areas outside the State. The Wharton Tract was acquired by the State in 1954 as a State Forest, Park, and water-reserve area. It lies outside, but close to, the Delaware River basin.

Barksdale (1952) was one of the first to discuss, from the viewpoint of the hydrologist, the potential value of the Pine Barrens for development of ground-water supply in New Jersey. He estimated that more than 1,000 mgd could be developed by a properly designed network of wells. The present writers believe that this estimated quantity may be possible of development, but not probable; 600-700 mgd would be more likely feasible of perennial development.

In the T-A-M-S report (Tippetts-Abbett-McCarthy-Stratton, 1955, p. III-13 - III-16) Leggette, Brashears, and Graham recommend the emplacement of lines of wells in the Cohansey sand along the Mullica, Batsto, and Wading Rivers, to induce recharge and to derive the optimum quantity of ground water from that part of the Wharton Tract. The water derived from the Mullica-Batsto wells could be diverted to the Camden area by a proposed aqueduct. Water from wells along the Wading River could be diverted to the shore area.

Similar developments of wells in the Cohansey sand in the drainage basins of Great Egg Harbor River and Toms River would undoubtedly provide important quantities of ground water. Some equitable division of these waters may be required eventually, in order to supply the needs of the local inhabitants, the nearby growing shore area, and the industrialized communities of the Delaware River basin.

Developments of water of this kind, and on the large scale envisioned above, would reduce streamflow from each stream basin so developed. In some places induced recharge would take water from the streams and in others ground-water pumping would reduce the discharge from the aquifers into the streams. Thus, riparian rights, or existing ground-water rights (not on streams) might well be interfered with; also, reduced flow in coastal streams would result in salt-water encroachment in their tidal reaches (unless salt-water barriers or other protective works were employed in the seaward ends of the streams). Such possible large-scale developments may, therefore, have far-reaching effects and would doubtless involve not only hydrologic and economic factors, but legal factors as well.

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Table 1.--Physical and hydrologic properties of the geologic formations and units in the D

[Formations of Paleozoic age listed are those that occur in the Valley and Ridge province, or New England province in east table 6. Cross hatched pattern between formations or units indicates hiatus or unconformity; formations or units separat

Stratigraphic assignment or age					Formation or unit	Maximum thickness (feet)	Physical properties
Era	System or period	Absolute age (millions of years) 1/	Series or epoch	Group or age equivalent			
	Quaternary	0-1	Recent		Beach and dune sand 2/	80	Well-sorted loose white and gray sand along shore bars.
					Marsh and swamp deposits 2/	30	Dark clay, silt, and organic matter in mars bordering streams, lakes, estuaries, and
					Alluvium 2/	50 ±	Unconsolidated stream deposits ranging from gravel. Not distinguishable from underly outwash where present.
			Pleistocene	Wisconsin stage	Glacial outwash 3/	400 ±	Elongate, narrow masses of unconsolidated d of glacial melt-water origin, filling str existed in glacial and preglacial times. some lake deposits and a few small masses and morainal deposits. Materials range i boulders deposited by melt-water streams silt and clay particles deposited in lake In some parts of basin, not differentiate fied glacial drift of uplands (pl. 30).
					Stratified glacial drift of uplands 3/	500 ±	Includes dissected glacial-outwash fills, r kame terraces, and kames, eskers, and del deposits are generally similar to those d glacial outwash from which they are disti chiefly by their higher topographic posit
					Glacial till 3/	350 ±	Heterogeneous, unsorted deposits ranging fr particles to boulders. Forms a discontin regular blanket over the glaciated norther basin. Usual thickness ranges from a few tens of feet; rare masses thicker than 10 occur in valleys where such masses are in glacial outwash or are plastered against valley walls.
					Terminal and recessional moraines 3/	250 +	Heterogeneous unsorted materials forming e sinuous ridges deposited at the margins stage ice sheet. Except for distinctive form and greater thickness, generally si cial till, but contain more sand and gra
					Basin-rim sand	30	Forms rims and, in places, interiors of sm elliptical, basins throughout Coastal Pl fine-grained sand and silt; lower part, dish brown poorly sorted coarse-grained
				Illinoian and Kansan stages	Early glacial drift	150 ±	Stratified and nonstratified glacial depo Jerseyan drift. Owing to their greater posits are more highly weathered and the more clay and silt from Wisconsin deposi origin. Not differentiated from Wiscons except south of limit of Wisconsin glaci

ydrologic properties of the geologic formations and units in the Delaware River basin TABLE I

in the Valley and Ridge province, or New England province in eastern Pennsylvania, equivalent formations in other areas are shown in units indicates hiatus or unconformity; formations or units separated by dashed lines are considered as single hydrologic units.]

r unit	Maximum thickness (feet)	Physical properties	Hydrologic properties
d 2/	80	Well-sorted loose white and gray sand along beaches and offshore bars.	Accepts recharge readily and in places contains fresh water sufficient for development of small supplies.
d its 2/	30	Dark clay, silt, and organic matter in marshes and swamps bordering streams, lakes, estuaries, and bays.	Saturated and frequently covered with water which in estuaries and bays near the ocean is more or less saline; permeability generally moderate to low.
2/	50 ±	Unconsolidated stream deposits ranging from clay to coarse gravel. Not distinguishable from underlying glacial outwash where present.	Water occurs under unconfined to locally semiconfined or confined conditions and, at most places near surface-water bodies, is hydraulically connected with them. Potentially a highly productive aquifer, especially in major stream valleys such as the upper reaches and tributaries of the Delaware River and of the Delaware River near Trenton, N. J. Where relatively thick bodies of sand and gravel are available, well yields of several thousand gallons per minute may be obtained, derived in part from streams as induced recharge. Quality of water is generally good, although concentration of dissolved iron is high in places. Bank storage in these deposits may significantly affect streamflow regimen.
ash 3/	400 ±	Elongate, narrow masses of unconsolidated deposits, largely of glacial melt-water origin, filling stream valleys that existed in glacial and preglacial times. Includes also some lake deposits and a few small masses of glacial till and morainal deposits. Materials range in grain size from boulders deposited by melt-water streams to fine-grained silt and clay particles deposited in lakes and marshes. In some parts of basin, not differentiated from stratified glacial drift of uplands (pl. 30).	
ied rift 3/	500 ±	Includes dissected glacial-outwash fills, river terraces, kame terraces, and kames, eskers, and deltas. These deposits are generally similar to those described as glacial outwash from which they are distinguished chiefly by their higher topographic position.	Many springs issue from these deposits, and substantial supplies of water may be obtained in the thicker masses from both springs and wells.
ill 3/	350 ±	Heterogeneous, unsorted deposits ranging from clay particles to boulders. Forms a discontinuous, irregular blanket over the glaciated northern part of the basin. Usual thickness ranges from a few feet to a few tens of feet; rare masses thicker than 100 feet generally occur in valleys where such masses are interbedded with glacial outwash or are plastered against bedrock of valley walls.	Generally not a dependable source of water supply because of limited thickness and low permeability. In many areas springs are common at contact with underlying bedrock, which suggests that much of the contained water is perched or semiperched.
and al 3/	250 +	Heterogeneous unsorted materials forming elongate, sinuous ridges deposited at the margins of the Wisconsin-stage ice sheet. Except for distinctive topographic form and greater thickness, generally similar to glacial till, but contain more sand and gravel.	Moraines function as moderately permeable intake areas for water transmitted to underlying rocks. Water-yielding capability not well known; presumably moderately large supplies could be produced by modern wells drilled in the thicker and coarser parts of the moraines. Chemical quality of water probably good for most purposes.
sand	30	Forms rims and, in places, interiors of small, generally elliptical, basins throughout Coastal Plain. Upper part, fine-grained sand and silt; lower part, deposit of reddish brown poorly sorted coarse-grained sand and gravel.	Basin rims deflect runoff to basin centers where infiltrations may occur, or, where underlying materials are saturated, large amounts of water may be lost by evapotranspiration. Some basins may discharge water by evapotranspiration during summer but may act as points of recharge to regional water table during nongrowing season.
rift	150 ±	Stratified and nonstratified glacial deposits, including Jerseyan drift. Owing to their greater age these deposits are more highly weathered and therefore contain more clay and silt from Wisconsin deposits of similar origin. Not differentiated from Wisconsin deposits except south of limit of Wisconsin glaciation (pl. 14).	Generally less permeable than younger glacial deposits of similar origin.

Era	System	Age	Series		Formation	Thickness	Description
CENOZOIC	Qu		Pleistocene	Illinoian and Kansan stages	Early glacial drift	150 ±	Stratified and nonstratified glacial dep Jerseyan drift. Owing to their greate posits are more highly weathered and t more clay and silt from Wisconsin depo origin. Not differentiated from Wisco except south of limit of Wisconsin gla
				Columbia group	Talbot and Cape May formations 4/	100 +	Form a roughly wedge-shaped mass thinni having tonguelike extensions up larger At their upper ends these tongues were with later glacial outwash by stream c Wisconsin glacial stage. Consist of r weathered stream-deposited sand and gr ward coast, in upper part, silt and cl in estuarine and marine environments.
					Unclassified deposits 5/		In Delaware topographically higher, but Talbot formation, and at least partly the Wicomico formation. In New Jersey posits, not shown on plate 6, topograph stratigraphically between the Bridgeto formation and the Cape May formation, sandy deposits not unlike weathered par underlying formations of Cretaceous an
					Pensauken formation	70	Blanketlike stream-laid and deltaic depos on broad ridges and terraces; topograph younger than the generally similar Brid Largely fills valleys cut in the Bridge formations.
					Bridgeton formation		Remnant of a blanketlike, chiefly stream- found only as outliers capping broad, ridges and hills; topographically above the Pensauken formation. Lenticular be brown, or red gravel, sand, and silt wh ally somewhat more weathered than simil the Pensauken formation. In some place large boulders that probably were rafte present position.
	Tertiary	1-10	Pliocene(?)		Bryn Mawr and Beacon Hill gravels	20	Semiconsolidated weathered gravelly depos the highest hills in the Coastal Plain and Piedmont (Bryn Mawr gravel).
			Miocene(?)		Cohansey sand	265	Quartzose sand, lenses of silt and clay thick, and some gravel. Probably delt possible grading toward coast into mar is generally somewhat micaceous, well coarse grained, white or light gray to lowish-brown, or orange, and is locall Silt and clay also are light colored, colors typical of silt and clay in und formation.
		10-25	Miocene	Middle Miocene	Kirkwood formation	700 +	Alternating beds of micaceous, quartzose [illegible] or silty sand, at tops of formation in Downdip toward the coast proportion of creases, but beds of sand become coars permeable. Beds of clay and silt, est tute at least four-fifths of total thi City, N. J., are blue, gray, and brown fossils, especially diatoms. Probably
		25-40	Oligocene				
		40-60	Eocene	Upper Eocene	Piney Point formation	290	Coarse- to fine-grained glauconitic sand colored, and greenish-gray clay. Fossi
				Middle Eocene	Shark River marl	200	In outcrop, a mixture of glauconite and in which uppermost 2-3 feet is cemente
				Lower Eocene	Manasquan marl		In outcrop, lower part chiefly glauconit upper part an ashy mixture of very fin and greenish-white clay. Marine.
			Paleocene	CAS GROUP	Vincentown sand	260	Limy sand, fossiliferous and somewhat con quartz sand containing some glauconite. grade southeastward to beds richer in ite. Marine.

nd	30	Forms rims and, in places, interiors of small, generally elliptical, basins throughout Coastal Plain. Upper part, fine-grained sand and silt; lower part, deposit of reddish brown poorly sorted coarse-grained sand and gravel.	tions may occur, or, where underlying materials are saturated, large amounts of water may be lost by evapotranspiration. Some basins may discharge water by evapotranspiration during summer but may act as points of recharge to regional water table during nongrowing season.
t	150 ±	Stratified and nonstratified glacial deposits, including Jerseyan drift. Owing to their greater age these deposits are more highly weathered and therefore contain more clay and silt from Wisconsin deposits of similar origin. Not differentiated from Wisconsin deposits except south of limit of Wisconsin glaciation (pl. 14).	Generally less permeable than younger glacial deposits of similar origin.
/	100 +	Form a roughly wedge-shaped mass thinning inland and having tonguelike extensions up larger stream valleys. At their upper ends these tongues were complexly mixed with later glacial outwash by stream currents of the Wisconsin glacial stage. Consist of relatively unweathered stream-deposited sand and gravel and, toward coast, in upper part, silt and clay deposited in estuarine and marine environments.	Inland portion contains unconfined water, but seaward portion contains water confined by upper member of silt and clay. Channel-fill deposits of highly permeable sand and gravel locally yield 1,000 gpm or more to modern drilled wells. Water is generally of excellent chemical quality but formation is particularly subject to pollution or contamination from surface sources and to encroachment of saline water.
		In Delaware topographically higher, but older than the Talbot formation, and at least partly equivalent to the Wicomico formation. In New Jersey includes deposits, not shown on plate 6, topographically and stratigraphically between the Bridgeton or Pensauken formation and the Cape May formation, and silty or sandy deposits not unlike weathered parts of the underlying formations of Cretaceous and Tertiary age.	Constitute moderately to highly permeable blanketlike deposits which serve primarily to collect recharge from precipitation and transmit it to underlying aquifers in deposits of Cretaceous and Tertiary age. Also, where thick enough, furnishes small supplies of water of good chemical quality to wells for domestic and farm uses. Runoff from outcrop not flashy and includes a relatively high proportion of base, or ground-water, flow.
	70	Blanketlike stream-laid and deltaic deposits now chiefly on broad ridges and terraces; topographically below, but younger than the generally similar Bridgeton formation. Largely fills valleys cut in the Bridgeton and older formations.	
		Remnant of a blanketlike, chiefly stream-laid deposit now found only as outliers capping broad, gently sloping ridges and hills; topographically above, but older than the Pensauken formation. Lenticular beds of yellow, brown, or red gravel, sand, and silt which are generally somewhat more weathered than similar materials of the Pensauken formation. In some places contains large boulders that probably were rafted by ice to present position.	
nd avels	20	Semiconsolidated weathered gravelly deposits capping a few of the highest hills in the Coastal Plain (Beacon Hill gravel) and Piedmont (Bryn Mawr gravel).	Relatively unimportant hydrologically because of small extent and position above the zone of saturation at most places.
and	265	Quartzose sand, lenses of silt and clay as much as 40 feet thick, and some gravel. Probably deltaic and estuarine, possible grading toward coast into marine deposits. Sand is generally somewhat micaceous, well sorted, fine to coarse grained, white or light gray to pale yellow, yellowish-brown, or orange, and is locally iron cemented. Silt and clay also are light colored, in contrast to dark colors typical of silt and clay in underlying Kirkwood formation.	An aquifer of very large potential yield. Water is mostly unconfined, but is semiconfined to confined where lenses of silt and clay are extensive. Permeability high, probably exceeded only by some sand and gravel in the deposits of Pleistocene age. Modern wells of large diameter may yield 100 to 1,000 gpm, or even more, where thickness is substantial. uality of water is generally good, but aquifer is subject to encroachment of saline water along coast and along shores of bay. Runoff of streams crossing outcrop is largely from ground-water discharge, owing to gentle topography, high infiltration capacity of the soil, and high permeability and storage capacity of the aquifer.
a	700 +	Alternating beds of micaceous, quartzose sand and silt or clay. Shiloh marl member, a highly fossiliferous clayey or silty sand, at tope of formation in souther New Jersey. Downdip toward the coast proportion of silt and clay increases, but beds of sand become coarser grained and more permeable. Beds of clay and silt, estimated to constitute at least four-fifths of total thickness at Atlantic City, N. J., are blue, gray, and brown and contain many fossils, especially diatoms. Probably estuarine and marine.	A sequence of several aquifers and aquicludes. Water occurs mostly under confined or semiconfined conditions, except at some places in the outcrop, where it is unconfined. Most important aquifers include "800-foot" sand of Atlantic City area and Cheswold and Frederica aquifers of Delaware. These thicker aquifers yield more than 500 gpm to modern drilled wells of large diameter. Water is generally of good to excellent quality, although salt-water encroachment has occurred in parts of Salem, Cumberland, Cape May, and Ocean Counties, N. J.; content of iron and silica is troublesomely high in places. Runoff from clayey parts of outcrop probably is flashy but is much evener from sandy areas.
t	290	Coarse- to fine-grained glauconitic sand, salt-and-pepper colored, and greenish-gray clay. Fossiliferous; marine.	Potentially an important aquifer in southern part of basin. Within the basin exists only in subsurface and all water is confined.
marl	200	In outcrop, a mixture of glauconite and light silty clay in which uppermost 2-3 feet is cemented. Marine.	An aquiclude imperfectly confining the water in the Vincentown sand. May be more effective as an aquiclude downdip, where the thickness is greater. Runoff from outcrop moderately flashy.
arl		In outcrop, lower part chiefly glauconite (greensand); upper part an ashy mixture of very fine-grained sand and greenish-white clay. Marine.	
			A minor aquifer containing water under unconfined conditions in outcrop but under confined conditions downdip

5

			Paleocene	RANCOCAS GROUP	Vincentown sand	260	Limy sand, fossiliferous and somewhat c quartz sand containing some glauconit grade southeastward into beds richer ite. Marine.
					Hornerstown marl	55	Dark-green to greenish-black glauconite sand and clay generally similar to Na fossiliferous; marine.
MESOZOIC	Cretaceous	60 -125	Upper Cretaceous	Monmouth group	Red Bank sand	185	Sand, fairly coarse grained, yellow or crop, dark gray in subsurface. Lower and some glauconite. Missing in cent Jersey. An upper member in Monmouth Tinton sand member, consists of somew itic clayey sand. Both units marine.
					Navesink marl	55	Green glauconitic marly sand and clay a shells. Upper part contains higher p than lower part. In Delaware not dis Laurel sand. Marine.
					Mount Laurel sand	110	Glauconitic quartz sand; minor amount o northern Delaware where not readily di Navesink marl. Sand is medium to coar and pepper colored, unconsolidated to idated, in places cemented by iron oxi
				Matawan group	Wenonah sand		Micaceous quartz sand; local thin beds c Sand is slightly glauconitic, fine to or black where fresh, but weathering t red. Marine.
					Marshalltown formation	125	Greenish-black to black sandy clay and l glauconitic sand that become more abun subsurface somewhat difficult to disti town and Wenonah sands. Fossiliferous
					Englishtown sand	160	Quartz sand, fine-grained to pebbly; a f of clay and silt which become more abu southern and eastern areas and in uppe Sand is loose or slightly consolidated by iron oxide; white, yellow, and bro gray in subsurface. Missing in Delaw New Jersey. Lagoonal and marine.
					Woodbury clay	250 +	Black or bluish-black tough clay, somew glauconitic; upper part slightly sand laminated. Not recognized in Delawa
					Merchantville clay		Black or greenish-black glauconitic, mi erally greasy and massive; some silt sand, particularly in upper part. M
					Magothy formation		A seaward-thickening wedge of nonmarine several environments--stream, marsh, arine--and, in the upper part, local environments. Deposits consist of hi continuous beds of sand, clay, silt, Many-colored, tough clay is character fine- to coarse-grained sand, much of Lignite (brown coal) and pyrite (iron cally, and a few thin beds containing in seaward part of unit.
					Raritan formation	5,000 ±	
				Potomac group	Patapsco formation		
			Lower Cretaceous		Patuxent formation		
	Jurassic	125-150					
					Diabase	2,000 ±	Dark greenish-gray fine- to medium-gra consisting principally of plagioclas as sills and dikes intruding Triassi Sparsely fractured; weathers to larg Forms prominent ridges and hills.

marl		upper part an ashy mixture of very fine-grained sand and greenish-white clay. Marine.	downdip, where the thickness is greater. Runoff from outcrop moderately flashy.
wn	260	Limy sand, fossiliferous and somewhat consolidated, and quartz sand containing some glauconite. Beds of sand grade southeastward into beds richer in clay and glauconite. Marine.	A minor aquifer containing water under unconfined conditions in outcrop but under confined conditions downdip where overlain by Manasquan marl or by beds of clay in Kirkwood formation. Wells yield as much as 300 gpm from thicker parts of aquifer, but yields of 50-100 gpm are more common. Water is relatively hard and moderately high in dissolved-solids content and contains troublesome amount of iron in places. Outcrop is fairly permeable and provides substantial amount of ground-water discharge to sustain base flow of streams.
wn	55	Dark-green to greenish-black glauconite (greensand); some sand and clay generally similar to Navesink marl. Locally fossiliferous; marine.	Together with Navesink marl, forms imperfect aquiclude ranging in thickness from 35 to 70 feet. At some places sandy parts of Hornerstown yield small supplies of water for domestic use. Runoff from outcrop probably rather flashy.
	185	Sand, fairly coarse grained, yellow or reddish-brown in outcrop, dark gray in subsurface. Lower part contains clay and some glauconite. Missing in central and southern New Jersey. An upper member in Monmouth County, N. J., the Tinton sand member, consists of somewhat indurated glauconitic clayey sand. Both units marine.	A minor aquifer. Within the basin, not thick enough to be developed for more than domestic supplies, but outside the basin, an important producer in Monmouth and northwestern Ocean Counties, N. J.
	55	Green glauconitic marly sand and clay and a basal bed of shells. Upper part contains higher proportion of clay than lower part. In Delaware not distinguished from Mount Laurel sand. Marine.	Together with overlying Hornerstown marl forms an extensive though imperfect aquiclude having a combined thickness of 35-70 feet. In Delaware south of Chesapeake and Delaware Canal, forms a poorly productive aquifer in conjunction with Mount Laurel sand. Base-exchange properties of glauconite in Navesink and Hornerstown marls may soften water in adjacent aquifers. Runoff from outcrop probably rather flashy.
rel	110	Glauconitic quartz sand; minor amount of clay, except in northern Delaware where not readily distinguishable from Navesink marl. Sand is medium to coarse grained, salt-and pepper colored, unconsolidated to slightly consolidated, in places cemented by iron oxide. Marine.	In New Jersey, Wenonah and Mount Laurel sands together form an extensive minor aquifer. In Delaware, Mount Laurel sand forms a poor aquifer or an imperfect aquiclude in conjunction with Navesink marl. Beds of sand moderately to highly permeable; few beds of silt and clay poorly permeable. Properly located and constructed wells yield about 50 to 500 gpm. Water slightly or moderately hard and moderate in dissolved-solids content. Iron content variable, troublesomely high at some places. High porosity and infiltration capacity produce relatively large amount of ground water available for base flow in streams crossing outcrop.
		Micaceous quartz sand; local thin beds of silt and clay. Sand is slightly glauconitic, fine to medium grained, gray or black where fresh, but weathering to yellow, brown, or red. Marine.	
own on	125	Greenish-black to black sandy clay and lenticular beds of glauconitic sand that become more abundant downdip. In subsurface somewhat difficult to distinguish from Englishtown and Wenonah sands. Fossiliferous; marine.	A somewhat leaky aquiclude confining water in Englishtown sand. Functions as an aquiclude together with underlying Woodbury and Merchantville clays in Salem County, N. J., but has not been recognized farther southwest in Delaware. Sandy parts yield as much as 40 gpm to domestic wells. Runoff from outcrop probably rather flashy.
wn	160	Quartz sand, fine-grained to pebbly; a few lenses and seams of clay and silt which become more abundant downdip in southern and eastern areas and in upper part of formation. Sand is loose or slightly consolidated, locally cemented by iron oxide; white, yellow, and brown in outcrop, light gray in subsurface. Missing in Delaware and southernmost New Jersey. Lagoonal and marine.	Water unconfined in outcrop; confined downdip by overlying Marshalltown formation. Productivity of aquifer ranges between wide limits, depending on thickness and permeability of sand beds. Properly constructed modern wells may be expected to yield about 50-500 gpm.
	250 ±	Black or bluish-black tough clay, somewhat micaceous, not glauconitic; upper part slightly sandy and distinctly laminated. Not recognized in Delaware. Marine.	Woodbury and Merchantville clays together form the most extensive and impermeable aquiclude in the Coastal Plain. Aquiclude is important in protecting underlying aquifers in nonmarine sediments from contamination or from encroachment of salt water and also in restricting loss of water from those aquifers by upward leakage. A few wells tap sandy parts of Merchantville clay, but Woodbury clay is everywhere too impermeable to yield water to wells. Runoff from outcrop rapid and flashy because of low infiltration capacity of soils.
ls		Black or greenish-black glauconitic, micaceous clay, generally greasy and massive; some silt and fine-grained sand, particularly in upper part. Marine.	
	5,000 ±	A seaward-thickening wedge of nonmarine deposits representing several environments--stream, marsh, lagoonal, and estuarine--and, in the upper part, local near-shore marine environments. Deposits consist of highly lenticular, discontinuous beds of sand, clay, silt, and little gravel. Many-colored, tough clay is characteristic, as is light, fine- to coarse-grained sand, much of which is crossbedded. Lignite (brown coal) and pyrite (iron sulfide) occur locally, and a few thin beds containing shells are present in seaward part of unit.	A complex group of lenticular aquifers and aquicludes. Constitutes the most important present source of ground water in the basin. Subject to recharge induced from the Delaware River estuary, and, in northeastern New Jersey, from Raritan Bay. Permeability and transmissibility of sand beds are high, except in some places, such as in northern Delaware, where permeability of some of the sand is reduced substantially by its silt and clay content. Although well yields exceeding 1,000 gpm are common, and many wells yield [illegible] gpm. Lenticularity and variable permeability of sand aquifers create problems in location and design of wells. Chemical quality of native water is relatively good, but in several places water in the aquifers has been [illegible] surface sources, or by encroachment of [illegible] from Delaware River Estuary and Raritan Bay.

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REPORT ON THE COMPREHENSIVE SURVEY OF THE WATER RESOURCES OF TH--ETC(U)

DEC 60   F H OLMSTED, G G PARKER, W B KEIGHTON

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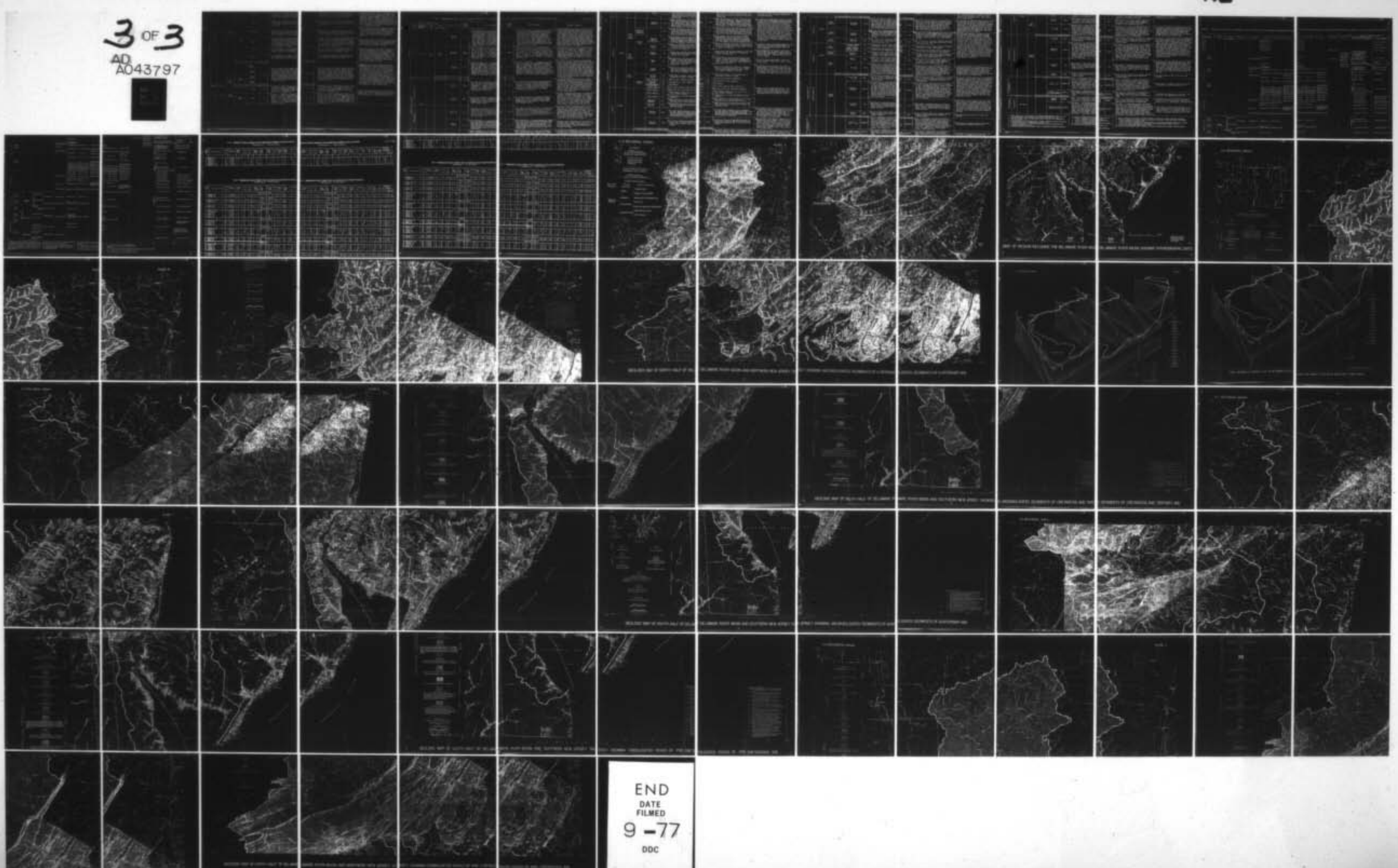

MESOZOIC	Cretaceous	60 -125	Upper Cretaceous		Mount Laurel sand	110	Glauconitic quartz sand; minor amount of c northern Delaware where not readily dist Navesink marl. Sand is medium to coarse and pepper colored, unconsolidated to sli idated, in places cemented by iron oxide
					Wenonah sand		Micaceous quartz sand; local thin beds of Sand is slightly glauconitic, fine to me or black where fresh, but weathering to red. Marine.
					Marshalltown formation	125	Greenish-black to black sandy clay and lent glauconitic sand that become more abundan subsurface somewhat difficult to distingu town and Wenonah sands. Fossiliferous; m
				Matawan group	Englishtown sand	160	Quartz sand, fine-grained to pebbly; a few of clay and silt which become more abunda southern and eastern areas and in upper p Sand is loose or slightly consolidated, l by iron oxide; white, yellow, and brown i gray in subsurface. Missing in Delaware New Jersey. Lagoonal and marine.
					Woodbury clay	250 +	Black or bluish-black tough clay, somewhat glauconitic; upper part slightly sandy an laminated. Not recognized in Delaware.
					Merchantville clay		Black or greenish-black glauconitic, micace erally greasy and massive; some silt and sand, particularly in upper part. Marine
					Magothy formation	5,000 ±	A seaward-thickening wedge of nonmarine dep several environments--stream, marsh, lago arine--and, in the upper part, local near environments. Deposits consist of highly continuous beds of sand, clay, silt, and Many-colored, tough clay is characteristi fine- to coarse-grained sand, much of whi Lignite (brown coal) and pyrite (iron sul cally, and a few thin beds containing she in seaward part of unit.
					Raritan formation		
				Potomac group	Patapsco formation		
			Lower Cretaceous		Patuxent formation		
	Jurassic	125-150					
	Triassic	150-180	Upper Triassic	Newark group	Diabase	2,000 ±	Dark greenish-gray fine- to medium-grained consisting principally of plagioclase an as sills and dikes intruding Triassic an Sparsely fractured; weathers to large ro Forms prominent ridges and hills.
					Basalt	900	Dark bluish- to greenish-gray fine-grained consisting principally of plagioclase an as flows interbedded with upper part of locally as small dikes. Broken by colum ing fractures into polygonal columns whi perpendicular to upper and lower surface prominent crescentic ridges, the Watchun northern New Jersey.

urel	110	northern Delaware where not readily distinguishable from Navesink marl. Sand is medium to coarse grained, salt- and pepper colored, unconsolidated to slightly consolidated, in places cemented by iron oxide. Marine.	form an extensive minor aquifer. In Delaware, Mount Laurel sand forms a poor aquifer or an imperfect aquiclude in conjunction with Navesink marl. Beds of sand moderately to highly permeable; few beds of silt and clay poorly permeable. Properly located and constructed wells yield about 50 to 500 gpm. Water slightly or moderately hard and moderate in dissolved-solids content. Iron content variable, troublesomely high at some places. High porosity and infiltration capacity produce relatively large amount of ground water available for base flow in streams crossing outcrop.
ah d		Micaceous quartz sand; local thin beds of silt and clay. Sand is slightly glauconitic, fine to medium grained, gray or black where fresh, but weathering to yellow, brown, or red. Marine.	
lltown tion	125	Greenish-black to black sandy clay and lenticular beds of glauconitic sand that become more abundant downdip. In subsurface somewhat difficult to distinguish from Englishtown and Wenonah sands. Fossiliferous; marine.	A somewhat leaky aquiclude confining water in Englishtown sand. Functions as an aquiclude together with underlying Woodbury and Merchantville clays in Salem County, N. J., but has not been recognized farther southwest in Delaware. Sandy parts yield as much as 40 gpm to domestic wells. Runoff from outcrop probably rather flashy.
town	160	Quartz sand, fine-grained to pebbly; a few lenses and seams of clay and silt which become more abundant downdip in southern and eastern areas and in upper part of formation. Sand is loose or slightly consolidated, locally cemented by iron oxide; white, yellow, and brown in outcrop, light gray in subsurface. Missing in Delaware and southernmost New Jersey. Lagoonal and marine.	Water unconfined in outcrop; confined downdip by overlying Marshalltown formation. Productivity of aquifer ranges between wide limits, depending on thickness and permeability of sand beds. Properly constructed modern wells may be expected to yield about 50-500 gpm.
ury	250 +	Black or bluish-black tough clay, somewhat micaceous, not glauconitic; upper part slightly sandy and distinctly laminated. Not recognized in Delaware. Marine.	Woodbury and Merchantville clays together form the most extensive and impermeable aquiclude in the Coastal Plain. Aquiclude is important in protecting underlying aquifers in nonmarine sediments from contamination or from encroachment of salt water and also in restricting loss of water from those aquifers by upward leakage. A few wells tap sandy parts of Merchantville clay, but Woodbury clay is everywhere too impermeable to yield water to wells. Runoff from outcrop rapid and flashy because of low infiltration capacity of soils.
rille		Black or greenish-black glauconitic, micaceous clay, generally greasy and massive; some silt and fine-grained sand, particularly in upper part. Marine.	
on on on	5,000 ±	A seaward-thickening wedge of nonmarine deposits representing several environments--stream, marsh, lagoonal, and estuarine--and, in the upper part, local near-shore marine environments. Deposits consist of highly lenticular, discontinuous beds of sand, clay, silt, and little gravel. Many-colored, tough clay is characteristic, as is light, fine- to coarse-grained sand, much of which is crossbedded. Lignite (brown coal) and pyrite (iron sulfide) occur locally, and a few thin beds containing shells are present in seaward part of unit.	A complex group of lenticular aquifers and aquicludes. Constitutes the most important present source of ground water in the basin. Subject to recharge induced from the Delaware River estuary, and, in northeastern New Jersey, from Raritan Bay. Permeability and transmissibility of sand beds are high, except in some places, such as in northern Delaware, where permeability of some of the sand is reduced substantially by its silt and clay content. Although well yields exceeding 1,000 gpm are common, and many wells yield 300-1,000 gpm, lenticularity and variable permeability of sand aquifers create problems in location and design of wells. Chemical quality of native water is relatively good, but in several places water in the aquifers has been contaminated from surface sources, or by encroachment of poor-quality water from Delaware River Estuary and Raritan Bay.
se	2,000 ±	Dark greenish-gray fine- to medium-grained crystalline rock consisting principally of plagioclase and augite. Occurs as sills and dikes intruding Triassic and older rocks. Sparsely fractured; weathers to large rounded boulders. Forms prominent ridges and hills.	Among the least favorable sources of water supplies in the basin. Only fractures contain water; porosity and permeability are very low. Unsuccessful wells are common, and the average yield of wells is less than 5 gpm.
lt	900	Dark bluish- to greenish-gray fine-grained crystalline rock consisting principally of plagioclase and augite. Occurs as flows interbedded with upper part of Newark group, and locally as small dikes. Broken by columnar joints or cooling fractures into polygonal columns which generally are perpendicular to upper and lower surfaces of flows. Forms prominent crescentic ridges, the Watchung Mountains, in northern New Jersey.	

Table 1.--Physical and hydrologic properties of the geologic formations and units in the Dela

Era	System or period	Absolute age (millions of years) 1/	Series or epoch	Group or age equivalent	Formation or unit	Maximum thickness (feet)	Physical properties
MESOZOIC	Triassic	150-180	Upper Triassic	Newark group	Brunswick formation 1/	7,000 ±	Soft red shale interbedded with smaller red siltstone and fine-grained sandsto yellow, gray, and purple shale and arg discontinuous lenses of sandstone and along northern border and also in an e south of Reading, Pa. Siltstone and s tively more abundant throughout format east, outside the basin. Near diabase fels, a hard, dark gray finely crystal altered shale forms elongate lowlands of more resistant rocks. Weathers mos composed of dark red clay loam.
					Lockatong formation 1/	3,800 ±	Chiefly thick-bedded dark-gray to black claystone or siltstone). Includes occ bedded dark shale, impure limestone an and in upper part, tongues of dark red red shale of type occurring in Brunswic which it is gradational. Argillite for where it is interbedded with softer sha where weaker zones are absent. Weather brown clay loam.
					Stockton formation 1/	5,000 ±	Light-gray or yellow medium- to coarse-gr stone containing much feldspar and some amounts of conglomerate, fine-grained r stone, and soft red shale. Lower part generally somewhat coarser grained than are commonly lenticular, although thick quences of beds may extend for many mil glomerate form ridges; soft red sandsto intervening valleys. Soils variable; s permeable on coarse-grained arkose and
	Permian	180-205					
	Carboniferous systems — Pennsylvanian	205-255			Allegheny formation	1,500 ±	Gray or brown shale and fine-grained sand cite coal, fire clay, and black carbona shale; scattered lenses of coarse-grain conglomerate. Coal beds are most persi are lenticular and change in character distances. In valleys surrounded by ca ridges; weathers to sandy loam.
					Pottsville formation	1,500	Hard quartzose conglomerate and coarse-gr few thin beds of coal and carbonaceous Becomes thinner and finer grained towar Conglomerate forms ridge enclosing coal lain by Allegheny formation.
	Carboniferous systems — Mississippian				Mauch Chunk formation	3,000 ±	Alternating lenticular beds of red shale some lenses of conglomerate in upper p thickest and coarsest in Schuylkill Co ward it thins abruptly and green shale prominent. Forms valleys between ridg and Pottsville formations; weathers to shallow to moderate depth.
					Pocono formation	1,600 ±	Gray or yellowish-gray hard quartzose san erate; some thin beds of greenish-gray green, gray, and red shale, and local t Like the Pottsville and Mauch Chunk for comes thinner and finer grained toward prominent ridges; weathers to stony soi moderate depth.
					Catskill		Somewhat lenticular beds of red, gray, or shale, and some conglomerate. Represen ing, probably delta deposit toward

r unit	Maximum thickness (feet)	Physical properties	Hydrologic properties
ck n 1/	7,000 ±	Soft red shale interbedded with smaller amounts of brownish-red siltstone and fine-grained sandstone, and green, yellow, gray, and purple shale and argillite. Includes discontinuous lenses of sandstone and conglomerate along northern border and also in an extensive area south of Reading, Pa. Siltstone and sandstone relatively more abundant throughout formation in the northeast, outside the basin. Near diabase, altered to hornfels, a hard, dark gray finely crystalline rock. Unaltered shale forms elongate lowlands between low ridges of more resistant rocks. Weathers mostly to thin soils composed of dark red clay loam.	Contains unconfined water in weathered part above a depth of about 250 feet and semiconfined to confined water in comparatively permeable zones rarely more than 20 feet thick from 250 to about 600 feet. Long-term yields of wells commonly are no more than one-third of the initial yield. Yields of drilled wells 300-600 feet deep range from about 25 to 500 gpm and are generally greatest in the northeast part of the Triassic Lowland, outside the basin. Water is moderately mineralized and moderately hard but is satisfactory for most uses without treatment. Runoff from outcrop is very flashy because of thin, poorly permeable soils and relatively small available ground-water storage capacity of the formation.
ng n 1/	3,800 ±	Chiefly thick-bedded dark-gray to black argillite (hard claystone or siltstone). Includes occasional zones of thin-bedded dark shale, impure limestone and limy argillite, and in upper part, tongues of dark red argillite and some red shale of type occurring in Brunswick formation, with which it is gradational. Argillite forms prominent ridges where it is interbedded with softer shale, and plateaus where weaker zones are absent. Weathers to thin yellowish-brown clay loam.	An unimportant source of water supply because of its very low porosity and permeability. verage yield of wells is only about 5-15 gpm. Water is moderately- to highly-mineralized and hard but does not commonly contain objectionable concentrations of any constituent except hardness-forming minerals. Runoff from outcrop is extremely flashy because of low permeability of thin soils and small ground-water storage capacity available to sustain base flow.
on ion 1/	5,000 ±	Light-gray or yellow medium- to coarse-grained arkose (sandstone containing much feldspar and some mica); smaller amounts of conglomerate, fine-grained red or brown sandstone, and soft red shale. Lower part of formation is generally somewhat coarser grained than upper part. Beds are commonly lenticular, although thicker beds and sequences of beds may extend for many miles. Arkose and conglomerate form ridges; soft red sandstone and shale form intervening valleys. Soils variable; are thickest and most permeable on coarse-grained arkose and conglomerate.	One of the most productive of the hard-rock formations. Most water occurs under confined or semiconfined conditions in weathered zone within about 500 feet of the land surface. Rocks having highest permeability are coarse-grained arkose and conglomerate which contain water in intergranular openings where original cementing material has been removed by weathering, as well as in fractures. Yields of modern drilled wells commonly exceed 50 gpm and may locally exceed 500 gpm. Water contains moderate concentrations of dissolved solids and hardness-forming minerals and is generally low in iron content; concentration of sulfate is high in places. Runoff from outcrop probably is less flashy than that from other formations of the Triassic Lowland.
ery ion	1,500 ±	Gray or brown shale and fine-grained sandstone; some anthracite coal, fire clay, and black carbonaceous slate or shale; scattered lenses of coarse-grained sandstone and conglomerate. Coal beds are most persistent; other beds are lenticular and change in character within short distances. In valleys surrounded by canoe-shaped ridges; weathers to sandy loam.	In coal-mining areas, unimportant as source of potable water because of high acidity of water resulting from oxidation of iron-sulfide minerals associated with coal and also because of extensive dewatering of formation in mining operations. In unmined areas, usually yields less than 100 gpm of water to wells; even this water commonly has high concentrations of dissolved iron and sulfate. Runoff characteristics of outcrop are not well known, are altered considerably from natural conditions by mining operations.
ille ion	1,500	Hard quartzose conglomerate and coarse-grained sandstone; a few thin beds of coal and carbonaceous slate or shale. Becomes thinner and finer grained toward the northeast. Conglomerate forms ridge enclosing coal basins underlain by Allegheny formation.	Fractures in conglomerate and sandstone contain water that is generally confined by beds of shale or slate or, in places, by unfractured coarse-grained rock. Many wells flow during at least part of the year. Most drilled wells tapping the Pottsville range in depth from 150 to 1,000 feet and yield 50-150 gpm of water which is suitable in quality for most purposes without treatment. Runoff from outcrop probably is at least moderately flashy because of rugged topography and thin soils.
nk n	3,000 ±	Alternating lenticular beds of red shale and green sandstone; some lenses of conglomerate in upper part. Formation is thickest and coarsest in Schuylkill County, Pa.; northward it thins abruptly and green shale becomes more prominent. Forms valleys between ridges held up by Pocono and Pottsville formations; weathers to silty soils of shallow to moderate depth.	Most important source of ground-water supplies in northeastern part of Valley and Ridge province within the basin. Receives ample recharge because of its low topographic position and yields 15-375 gpm to industrial and municipal wells 100-600 feet deep. Also an important and reliable source of domestic and farm supplies. Water in beds of sandstone is confined by less permeable beds of shale, and many deep wells flow. Water is low in dissolved-solids content and is soft. Runoff characteristics of outcrop are not well known.
no tion	1,600 ±	Gray or yellowish-gray hard quartzose sandstone and conglomerate; some thin beds of greenish-gray sandstone, yellow, green, gray, and red shale, and local thin beds of coal. Like the Pottsville and Mauch Chunk formations, it becomes thinner and finer grained toward the north. Forms prominent ridges; weathers to stony soils of shallow to moderate depth.	Potentially a productive formation, but little developed at present owing to rugged terrane of its outcrop. Some wells flow during the winter. Water appears to be of good chemical quality. Streamflow characteristics of outcrop not well known.
ill	[illegible] ±	Somewhat lenticular beds of red, gray, or green sandstone, shale, and some conglomerate. Represents a vast nonmarine, probably deltaic, deposit; toward the west, lower	Most extensive water-bearing unit within reach of wells in basin. Beds of coarse-grained sandstone generally more permeable than interbedded fine-grained sandstone

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					Pocono formation	1,600 ±	green, gray, and red shale, and local t Like the Pottsville and Mauch Chunk for comes thinner and finer grained toward prominent ridges; weathers to stony soi moderate depth.
PALEOZOIC	Devonian	255-315	Middle and Upper Devonian		Catskill formation 8/	6,000 ±	Somewhat lenticular beds of red, gray, or shale, and some conglomerate. Represent ine, probably deltaic, deposit; toward t part contains marine tongues equivalent Hamilton groups. Underlies most of Appa forms valleys and low ridges in Valley a
				Portage group, as used in Pennsylvania		1,500	Sandstone interbedded with sandy shale and is hard gray to greenish gray, thin to t micaceous; shale and sandy shale are gre gray to black, and locally fossiliferous Ridge province forms broad ridges having
				Hamilton group	Mahantango formation of Willard (1935)	1,600	Dark -gray shale, in part hard and slaty; flaggy sandstone, and sandy shale; thin shale; and in upper part a prominent bed ous impure limestone, known locally as th reef. Less resistant to erosion than ove
					Marcellus shale	900	Dark-gray to black shale, sandy shale, cl stone; some slaty shale in lower part. is covered by glacial outwash throughout northeast of Stroudsburg, Pa.
			Lower and Middle Devonian		Onondaga limestone	250	Dark-gray cherty limestone, shaly limesto Thins southwestward. Forms narrow low- weathers to dark clay loam.
					Esopus shale	375	Dark sandy shale and limy shale having pr cleavage. Coarsest and thickest in nor Jersey; thins toward the southwest in P toward the northeast in New York. Form tensive areas of bare rock.
			Lower Devonian		Oriskany sandstone	175	Granular quartz sandstone and fine-graine some sandy fossiliferous limestone, che Sandy limestone predominates in New Jer narrow ridges and weathers to sandy loa
				Helderberg group	Port Ewen limestone	190	In New Jersey and New York, poorly expose Pennsylvania now known to be present.
					Becraft limestone	20	Hard gray cherty limestone, fossiliferous
					New Scotland limestone	160	Limy shale and hard cherty limestone.
					Stormville sandstone of Weller (1900)	10	Limy sandstone.
					Coeymans limestone	75	Pure to sandy limestone, highly fossilif
	Silurian	315-350			Manlius limestone	35	Dark-blue to nearly black fossiliferous l
					Rondout limestone	40	Thinly laminated limestone; near top inc silty, dolomitic limestone.
					Decker limestone	90	In Pennsylvania, thick-bedded limy sandst limestone.
					Bossardsville limestone	100	Banded fine-grained bluish-gray limestone limestone in places having columnar str
					Wills Creek shale 9/	200 ±	Unfossiliferous buff, green, and variegat shale; hard bluish-gray fossiliferous c stone near the base.
					Bloomsburg red beds	2,000	Red or green shale and sandstone; a littl near base. Formation probably nonmarin Forms northwest slope of ridge known as Mountains in New York, Kittatinny Mount and Blue Mountain in Pennsylvania.
					Shawangunk conglomerate	1,900	Hard quartzitic sandstone and conglomerate beds of shale. Derives its name from a perhaps the most prominent ridge in the province.
							Upper 500 feet, well-sorted medium- to fi sandstone or graywacke, cemented in low um carbonate, and a few lenses of shale

on	1,600 ±	Like the Pottsville and Mauch Chunk formations, it becomes thinner and finer grained toward the north. Forms prominent ridges; weathers to stony soils of shallow to moderate depth.	wells flow during the winter. Water appears to be of good chemical quality. Streamflow characteristics of outcrop not well known.
8/	6,000 ±	Somewhat lenticular beds of red, gray, or green sandstone, shale, and some conglomerate. Represents a vast nonmarine, probably deltaic, deposit; toward the west, lower part contains marine tongues equivalent to Portage and Hamilton groups. Underlies most of Appalachian Plateaus; forms valleys and low ridges in Valley and Ridge province.	Most extensive water-bearing unit within reach of wells in basin. Beds of coarse-grained sandstone generally more permeable than interbedded fine-grained sandstone and shale, although in places beds of thin-bedded, flaggy sandstone and sandy shale in Catskill formation are reported to be good water producers. Reported yields of wells range from nearly 0 to 600 gpm; large deep drilled wells commonly yield more than 100 gpm. However, great variations in productivity, water levels, and chemical character of water are known to occur within short distances. Many wells flow, at least during the winter. Water is soft and low in dissolved-solids content but locally contains hydrogen sulfide and objectionable quantities of dissolved iron. Runoff from outcrop is moderately to highly flashy, depending in part on thickness and character of mantling glacial deposits.
	1,500	Sandstone interbedded with sandy shale and shale. Sandstone is hard gray to greenish gray, thin to thick bedded, and micaceous; shale and sandy shale are greenish or bluish gray to black, and locally fossiliferous. In Valley and Ridge province forms broad ridges having moderate relief.	
go n 935)	1,600	Dark -gray shale, in part hard and slaty; thin-bedded, flaggy sandstone, and sandy shale; thin beds of limy shale; and in upper part a prominent bed of fossiliferous impure limestone, known locally as the Centerfield reef. Less resistant to erosion than overlying formations.	
	900	Dark-gray to black shale, sandy shale, claystone, and siltstone; some slaty shale in lower part. Forms valleys and is covered by glacial outwash throughout most of outcrop northeast of Stroudsburg, Pa.	Yields small (1-25 gpm) but dependable domestic supplies of good water from fractures. Runoff probably is flashy except where overlying glacial deposits are thick and permeable.
	250	Dark-gray cherty limestone, shaly limestone, and limy shale. Thins southwestward. Forms narrow low-lying belt; weathers to dark clay loam.	Solution channels yield 20-100 gpm to drilled wells; fractured limestone lacking such channels yields only about 1-5 gpm. Water is hard, but softer than water from most limestones. Streamflow characteristics of outcrop not known.
	375	Dark sandy shale and limy shale having pronounced slaty cleavage. Coarsest and thickest in northwestern New Jersey; thins toward the southwest in Pennsylvania and toward the northeast in New York. Forms ridges with extensive areas of bare rock.	Hydrologic properties largely unknown. Runoff from outcrop is probably flashy owing to rugged topography and thin soils.
	175	Granular quartz sandstone and fine-grained conglomerate; some sandy fossiliferous limestone, chert, and shale. Sandy limestone predominates in New Jersey. Forms narrow ridges and weathers to sandy loam.	Granular sandstone and conglomerate contain small to moderate amounts of water between grains where cement has been removed by solution in weathered zone; elsewhere only very small quantities of water are contained in fractures. Few wells tap this formation because of its inextensive and rugged outcrop and its steep dip.
	190	In New Jersey and New York, poorly exposed shale; in Pennsylvania now known to be present.	Hydrologic properties largely unknown because of the scarcity of wells tapping these formations. Beds of limestone probably contain moderate quantities of water in joints and solution channels, whereas generally small amounts are contained in the shales.
one	20	Hard gray cherty limestone, fossiliferous.	
	160	Limy shale and hard cherty limestone.	
stone 00)	10	Limy sandstone.	
stone	75	Pure to sandy limestone, highly fossiliferous.	
tone	35	Dark-blue to nearly black fossiliferous limestone.	
tone	40	Thinly laminated limestone; near top includes a bed of silty, dolomitic limestone.	
tone	90	In Pennsylvania, thick-bedded limy sandstone and some limestone.	
	100	Banded fine-grained bluish-gray limestone and basal slaty limestone in places having columnar structure.	
	200 ±	Unfossiliferous buff, green, and variegated beds of limy shale; hard bluish-gray fossiliferous crystalline limestone near the base.	
s	2,000	Red or green shale and sandstone; a little conglomerate near base. Formation probably nonmarine, at least in part. Forms northwest slope of ridge known as Shawangunk Mountains in New York, Kittatinny Mountains in New Jersey, and Blue Mountain in Pennsylvania.	Beds of sandstone capable of yielding substantial supplies of water; shale beds are less permeable, on the average. A reliable source of supplies in Monroe County, Pa., where reported yields of 12 wells range from 2 to 200 gpm and average about 100 gpm. Water probably is moderately mineralized and fairly soft. Runoff from outcrop believed to be rather flashy.
t te	1,900	Hard quartzitic sandstone and conglomerate and a few thin beds of shale. Derives its name from and forms what is perhaps the most prominent ridge in the Valley and Ridge province.	Highly fractured, brittle quartzitic sandstone and conglomerate sufficiently permeable to yield 100-200 gpm or more to modern drilled wells. Water occurs under confined conditions, at least locally, and some wells flow. Water supplies are not extensively developed owing to rugged topography of its outcrop. Water is reported to be of excellent quality. Runoff from outcrop is probably flashy.
		Upper 500 feet, well-sorted medium- to fine-grained arkosic sandstone or graywacke, cemented in lower part by calcium carbonate, and a few lenses of shale and conglomerate. Lower 3,500 feet, banded bluish-gray shale and slate;	Shale yields small but dependable supplies of water, mostly from secondary openings in zone of weathered rock at depths of less than 200 feet. Sandstone may be somewhat more productive, on the average. Most wells

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							provin...
	Ordovician	350-430	Upper Ordovician		Martinsburg shale 10/	4,000 ±	Upper 500 feet, well-sorted medium- to fin... sandstone or graywacke, cemented in lowe... um carbonate, and a few lenses of shale ... Lower 3,500 feet, banded bluish-gray sha... some fine-grained limy sandstone and som... Forms the higher, more dissected and hil... Great Valley; weathers to an imperfectly... loam, at most places less than 3 feet th...
			Middle Ordovician		Jacksonburg limestone	700	Dark shaly or slaty impure limestone and ... shale which increase in abundance towar... Extensively quarried as "cement rock". ... margins of valleys; weathers to well-dr... red loam.
			Lower Ordovician		Beekmantown limestone	2,000	Gray to blue dolomite and dolomitic limes... ous and shaly beds. Forms valleys and ... drained yellowish-red loam.
	Cambrian	430-510	Upper Cambrian		Allentown limestone of Wherry (1909)	500	Alternating light and dark dolomitic lime... fossiliferous in places. Forms lowland...
					Limeport limestone of Howell, Roberts, and Willard (1950)	900	Alternating light- and dark-gray dolomiti... dolomite, abundantly fossiliferous. For...
			Middle(?) Cambrian		Leithsville formation	900	Thick-bedded dolomitic limestone and dolo... of finely micaceous shale. Grades upwa... limestone. Forms lowlands and low hill...
			Lower Cambrian		Tomstown dolomite	1,000 ±	Dolomite, thin-bedded and locally clayey ... citic shale, and thick-bedded dolomitic... Equivalent to Ledger dolomite, Kinzers ... Vintage dolomite of the Piedmont provin...
					Hardyston quartzite	200 ±	Comprises a variety of more or less quartz... cluding sandstone, conglomerate, quartzi... shale, and micaceous quartz schist. For... abrupt slopes at valley margins and weat... of gray to grayish-brown stony loam. Ap... equivalent to Antietam sandstone, Harper... Chickies quartzite of the Piedmont provi... as much as 1,500 feet in total thicknes...
PALEOZOIC (?)	Lower Paleozoic (?)		Glenarm series		Peters Creek schist	2,000	Micaceous quartzite and schist; a few thi... near top. Formation contains less feld... metamorphosed than the Wissahickon form... otherwise similar.
					Wissahickon formation	8,000 ±	Most widespread of the crystalline rocks ... province. Comprises schist, gneiss, ph... ite and includes masses of granitic to g... ultramafic rocks, and pegmatite dikes. ... most important minerals in the schist a... important constituents are feldspar, qu... and garnet. Consists mostly of metamor... ary rocks but includes also some rocks ... Degree of metamorphism increases southe... dissected upland; weathers to yellow, b... soils which are thick on broad interstr... thin on steep slopes.
					Cockeysville marble	200 +	Massive medium- to coarse-grained white to... sugary marble, in places containing lens... schist. Scattered, irregular exposures ... Piedmont province. Weathered zone of cl... thicker than 50 feet.
					Setters formation	1,000	Quartzite, quartzitic schist, and mica gne... ridges and slopes bordering valleys unde... Cockeysville marble.
PRECAMBRIAN AND PALEOZOIC					Granitic to gabbroic rocks	Indefinite	Medium- to coarse-grained crystalline rock... granite, quartz monzonite, granodiorite, ... diorite, anorthosite, and gabbro; common... gneissose; locally massive, not differen... various gneisses of Precambrian age, or ... series, where intimately or gradationally... those units. Probably of both igneous ... origin. Forms gently rolling to hilly ... weathers to sandy clay or clay.
					Ultramafic rocks including serpentine	Indefinite	Chiefly serpentine, metapyroxenite, and me... small masses at scattered localities in ... Upland. Forms barren, rocky outcrops or... ridges.

		province.	flow. Water supplies are not extensively developed owing to rugged topography of its outcrop. Water is reported to be of excellent quality. Runoff from outcrop is probably flashy.
s	4,000 ±	Upper 500 feet, well-sorted medium- to fine-grained arkosic sandstone or graywacke, cemented in lower part by calcium carbonate, and a few lenses of shale and conglomerate. Lower 3,500 feet, banded bluish-gray shale and slate; some fine-grained limy sandstone and some red beds. Forms the higher, more dissected and hilly part of the Great Valley; weathers to an imperfectly drained clay loam, at most places less than 3 feet thick.	Shale yields small but dependable supplies of water, mostly from secondary openings in zone of weathered rock at depths of less than 200 feet. Sandstone may be somewhat more productive, on the average. Most wells yield less than 50 gpm, but a few yield 100-250 gpm. Water generally contains less than 200 ppm of dissolved solids and has a hardness of less than 100 ppm. Iron content rarely exceeds 1 ppm but is noticeable at some places. Runoff from outcrop is very flashy.
:	700	Dark shaly or slaty impure limestone and thin beds of limy shale which increase in abundance toward top of formation. Extensively quarried as "cement rock". Forms slopes at margins of valleys; weathers to well-drained yellowish-red loam.	Water occurs under unconfined to confined conditions, almost entirely in fractures and solution openings. Occurrence of these secondary openings is extremely irregular and difficult to predict, although, in general, solution openings are most abundant near streams and least abundant in the shaly formations or parts of formations. Most solution openings occur between depths of 50 and about 300 feet, although some openings deeper than 1,000 feet are reported. Yields of wells in the carbonate rocks range more widely than in any other aquifers in the basin; yields of from less than 5 to nearly 1,500 gpm are reported, although few wells produce more than 500 gpm. Most of the water is moderately to very hard and contains moderate amounts of dissolved mineral matter. Softening is required for some uses. Runoff from outcrop includes a relatively high proportion of ground-water discharge and ranks with runoff from sandy parts of Coastal Plain in having the least flashy character in the basin.
ı	2,000	Gray to blue dolomite and dolomitic limestone, some siliceous and shaly beds. Forms valleys and weathers to well-drained yellowish-red loam.	
tone 9)	500	Alternating light and dark dolomitic limestone, abundantly fossiliferous in places. Forms lowlands.	
ne ts, o)	900	Alternating light- and dark-gray dolomitic limestone and dolomite, abundantly fossiliferous. Forms lowlands.	
	900	Thick-bedded dolomitic limestone and dolomite; many beds of finely micaceous shale. Grades upward into Limeport limestone. Forms lowlands and low hills.	
	1,000 −	Dolomite, thin-bedded and locally clayey or shaly, sericitic shale, and thick-bedded dolomitic limestone. Equivalent to Ledger dolomite, Kinzers formation, and Vintage dolomite of the Piedmont province.	
ı	200 ±	Comprises a variety of more or less quartzose rocks, including sandstone, conglomerate, quartzite, chert, hard shale, and micaceous quartz schist. Forms ridges or abrupt slopes at valley margins and weathers to thin soils of gray to grayish-brown stony loam. Approximately equivalent to Antietam sandstone, Harpers schist, and Chickies quartzite of the Piedmont province which are as much as 1,500 feet in total thickness.	Not sufficiently extensive to be developed very much for ground-water supplies. Most abundant water is in highly fractured zones near faults and near contacts with underlying gneiss. Water is low in dissolved-solids content and very soft. Most drilled wells in the Chickies quartzite of the Piedmont province are less than 200 feet deep and yield about 5-20 gpm.
k	2,000	Micaceous quartzite and schist; a few thin beds of sandstone near top. Formation contains less feldspar and is less metamorphosed than the Wissahickon formation but is otherwise similar.	Contains water in open fractures and also in intergranular pore spaces in weathered zone. Porosity and permeability generally decrease with depth so that, with few exceptions, little water can be obtained below about 300 feet. Drilled wells used for municipal or industrial supplies yield 20-100 gpm or even more; most drilled domestic wells will yield 2-20 gpm. Water usually contains less than 150 gpm of dissolved solids and is very soft, but in a few places it has objectionable quantities of dissolved iron. Owing in large part to the moderately high infiltration capacity of the soils and the comparatively large available ground water storage capacity in the thick weathered zone, about two-thirds of the runoff from the outcrop consists of base flow--largely ground-water discharge.
ı	8,000 ±	Most widespread of the crystalline rocks in the Piedmont province. Comprises schist, gneiss, phyllite, and quartzite and includes masses of granitic to gabbroic rocks, ultramafic rocks, and pegmatite dikes. Micas are the most important minerals in the schist and gneiss; other important constituents are feldspar, quartz, chlorite, and garnet. Consists mostly of metamorphosed sedimentary rocks but includes also some rocks of igneous origin. Degree of metamorphism increases southeastward. Forms dissected upland; weathers to yellow, brown, or red soils which are thick on broad interstream areas but thin on steep slopes.	
e	200 +	Massive medium- to coarse-grained white to bluish-gray sugary marble, in places containing lenses of limy mica schist. Scattered, irregular exposures in valleys in Piedmont province. Weathered zone of clay is commonly thicker than 50 feet.	Contains water in solution openings, joints, and, especially in lenses of limy schist, between grains. Thick weathered zone also contains substantial quantities of water. Like most carbonate rocks, it is an erratic water producer. Some wells reported yield 100-400 gpm; but others in zones where fractures and solution openings are scarce or absent may yield only a few gallons per minute. Water is hard and requires softening for some uses.
	1,000	Quartzite, quartzitic schist, and mica gneiss. Forms low ridges and slopes bordering valleys underlain by Cockeysville marble.	Yields small supplies of water of good quality from fractures.
ks	Indefinite	Medium- to coarse-grained crystalline rocks including granite, quartz monzonite, granodiorite, quartz diorite, diorite, anorthosite, and gabbro; commonly somewhat gneissose; locally massive, not differentiated from various gneisses of Precambrian age, or from Glenarm series, where intimately or gradationally associated with those units. Probably of both igneous and metamorphic origin. Forms gently rolling to hilly uplands; weathers to sandy clay or clay.	Contains water in fractures and, near the land surface, in intergranular openings in weathered rock.
cks ntine	Indefinite	Chiefly serpentine, metapyroxenite, and metaperidotite; small masses at scattered localities in Piedmont Upland. Forms barren, rocky outcrops on low hills and	Contains small quantities of water in fractures. Water is hard and of the magnesium bicarbonate type.

Era	System	Age (million years)	Series		Formation	Thickness (feet)	Description
	Cambrian	430-510	Cambrian		formation	900	of finely micaceous shale. Grades ... limestone. Forms lowlands and low hi
			Lower Cambrian		Tomstown dolomite	1,000 ±	Dolomite, thin-bedded and locally claye citic shale, and thick-bedded dolomit Equivalent to Ledger dolomite, Kinzer Vintage dolomite of the Piedmont prov
					Hardyston quartzite	200 ±	Comprises a variety of more or less quar cluding sandstone, conglomerate, quar shale, and micaceous quartz schist. abrupt slopes at valley margins and we of gray to grayish-brown stony loam. equivalent to Antietam sandstone, Harp Chickies quartzite of the Piedmont pro as much as 1,500 feet in total thickne
PALEOZOIC (?)	Lower Paleozoic (?)		Glenarm series		Peters Creek schist	2,000	Micaceous quartzite and schist; a few t near top. Formation contains less fe metamorphosed than the Wissahickon fo otherwise similar.
					Wissahickon formation	8,000 ±	Most widespread of the crystalline rock province. Comprises schist, gneiss, ite and includes masses of granitic to ultramafic rocks, and pegmatite dikes most important minerals in the schis important constituents are feldspar, and garnet. Consists mostly of metam ary rocks but includes also some rock Degree of metamorphism increases sout dissected upland; weathers to yellow, soils which are thick on broad inters thin on steep slopes.
					Cockeysville marble	200 +	Massive medium- to coarse-grained white sugary marble, in places containing le schist. Scattered, irregular exposure Piedmont province. Weathered zone of thicker than 50 feet.
					Setters formation	1,000	Quartzite, quartzitic schist, and mica ridges and slopes bordering valleys u Cockeysville marble.
PRECAMBRIAN AND PALEOZOIC					Granitic to gabbroic rocks	Indefinite	Medium- to coarse-grained crystalline r granite, quartz monzonite, granodiorit diorite, anorthosite, and gabbro; com gneissose; locally massive, not differ various gneisses of Precambrian age, series, where intimately or gradational those units. Probably of both igneou origin. Forms gently rolling to hill weathers to sandy clay or clay.
					Ultramafic rocks including serpentine	Indefinite	Chiefly serpentine, metapyroxenite, and small masses at scattered localities Upland. Forms barren, rocky outcrops ridges.
PRECAMBRIAN	Precambrian	510-4,500±			Franklin limestone	Unknown	Coarse- to fine-grained marble or dolom cally containing graphite and other mi masses associated with gneiss of Preca
					Gneiss and related crystalline rocks	Indefinite	Mostly medium- to coarse-grained gneisso from light-colored rocks having abunda spar to dark rocks containing abundant bearing minerals. Include rocks of me igneous, and igneous origin, and compl types. Comprise Pochuck gabbro gneis gneiss, Byram granite gneiss, Pickerin gneisses, and several kinds of unnamed tly rolling to hilly uplands; weather

1/ Figures adopted by U. S. Geological Survey, Geologic Names Committee, 1958, except for age of Precambrian, which is based on an estimate by Harrison Brown (1957).
2/ Beach and dune sand, marsh and swamp deposits, and alluvium are all contemporaneous, at least in part.
3/ Glacial outwash, stratified glacial drift of uplands, terminal and recessional moraines, and glacial till are all contemporaneous, at least in part.
4/ In vicinity of Trenton, N. J., Cape May formation has not been differentiated with certainty from glacial outwash.
5/ Unclassified deposits may be equivalent in part to Pensauken and Bridgeton formations.

6/ Raritan formation of New Jersey m
7/ Brunswick, Lockatong, and Stockto units, by McLaughlin (in Greenma
8/ Catskill formation now considered In places it includes equivalen
9/ Locally called Pocono Island shal
10/ Martinsburg shale has been called

A

	900	of finely micaceous shale. Grades upward into Limeport limestone. Forms lowlands and low hills.	from sandy parts of Coastal Plain in having the least flashy character in the basin.
	1,000 –	Dolomite, thin-bedded and locally clayey or shaly, sericitic shale, and thick-bedded dolomitic limestone. Equivalent to Ledger dolomite, Kinzers formation, and Vintage dolomite of the Piedmont province.	
	200 ±	Comprises a variety of more or less quartzose rocks, including sandstone, conglomerate, quartzite, chert, hard shale, and micaceous quartz schist. Forms ridges or abrupt slopes at valley margins and weathers to thin soils of gray to grayish-brown stony loam. Approximately equivalent to Antietam sandstone, Harpers schist, and Chickies quartzite of the Piedmont province which are as much as 1,500 feet in total thickness.	Not sufficiently extensive to be developed very much for ground-water supplies. Most abundant water is in highly fractured zones near faults and near contacts with underlying gneiss. Water is low in dissolved-solids content and very soft. Most drilled wells in the Chickies quartzite of the Piedmont province are less than 200 feet deep and yield about 5-20 gpm.
k	2,000	Micaceous quartzite and schist; a few thin beds of sandstone near top. Formation contains less feldspar and is less metamorphosed than the Wissahickon formation but is otherwise similar.	Contains water in open fractures and also in intergranular pore spaces in weathered zone. Porosity and permeability generally decrease with depth so that, with few exceptions, little water can be obtained below about 300 feet. Drilled wells used for municipal or industrial supplies yield 20-100 gpm or even more; most drilled domestic wells will yield 2-20 gpm. Water usually contains less than 150 gpm of dissolved solids and is very soft, but in a few places it has objectionable quantities of dissolved iron. Owing in large part to the moderately high infiltration capacity of the soils and the comparatively large available ground water storage capacity in the thick weathered zone, about two-thirds of the runoff from the outcrop consists of base flow--largely ground-water discharge.
	8,000 ±	Most widespread of the crystalline rocks in the Piedmont province. Comprises schist, gneiss, phyllite, and quartzite and includes masses of granitic to gabbroic rocks, ultramafic rocks, and pegmatite dikes. Micas are the most important minerals in the schist and gneiss; other important constituents are feldspar, quartz, chlorite, and garnet. Consists mostly of metamorphosed sedimentary rocks but includes also some rocks of igneous origin. Degree of metamorphism increases southeastward. Forms dissected upland; weathers to yellow, brown, or red soils which are thick on broad interstream areas but thin on steep slopes.	
e	200 +	Massive medium- to coarse-grained white to bluish-gray sugary marble, in places containing lenses of limy mica schist. Scattered, irregular exposures in valleys in Piedmont province. Weathered zone of clay is commonly thicker than 50 feet.	Contains water in solution openings, joints, and, especially in lenses of limy schist, between grains. Thick weathered zone also contains substantial quantities of water. Like most carbonate rocks, it is an erratic water producer. Some wells reported yield 100-400 gpm; but others in zones where fractures and solution openings are scarce or absent may yield only a few gallons per minute. Water is hard and requires softening for some uses.
	1,000	Quartzite, quartzitic schist, and mica gneiss. Forms low ridges and slopes bordering valleys underlain by Cockeysville marble.	Yields small supplies of water of good quality from fractures.
ks	Indefinite	Medium- to coarse-grained crystalline rocks including granite, quartz monzonite, granodiorite, quartz diorite, diorite, anorthosite, and gabbro; commonly somewhat gneissose; locally massive, not differentiated from various gneisses of Precambrian age, or from Glenarm series, where intimately or gradationally associated with those units. Probably of both igneous and metamorphic origin. Forms gently rolling to hilly uplands; weathers to sandy clay or clay.	Contains water in fractures and, near the land surface, in intergranular openings in weathered rock.
cks ntine	Indefinite	Chiefly serpentine, metapyroxenite, and metaperidotite; small masses at scattered localities in Piedmont Upland. Forms barren, rocky outcrops on low hills and ridges.	Contains small quantities of water in fractures. Water is hard and of the magnesium bicarbonate type.
	Unknown	Coarse- to fine-grained marble or dolomitic marble locally containing graphite and other minerals. Small masses associated with gneiss of Precambrian age.	Contains small to moderate quantities of hard water in joints and generally sparse solution openings. Not a significant source of water because of its limited extent.
lated ocks	Indefinite	Mostly medium- to coarse-grained gneissose rocks ranging from light-colored rocks having abundant quartz and feldspar to dark rocks containing abundant iron- and magnesium-bearing minerals. Include rocks of metasedimentary, metaigneous, and igneous origin, and complex mixtures of these types. Comprise Pochuck gabbro gneiss, Losee diorite gneiss, Byram granite gneiss, Pickering and Baltimore gneisses, and several kinds of unnamed gneiss. Form gently rolling to hilly uplands; weather to sandy clay or clay.	Contain water in weathered and fractured zones. As in other crystalline rocks, porosity and permeability generally decrease with depth. Generally similar to Wissahickon formation in well yields, chemical character of water, and streamflow characteristics of outcrop.

58, except for
957).
mporaneous,
sional moraines,
lated with
on formations.

6/ Raritan formation of New Jersey may include equivalents of Patapsco and Patuxent formations of Delaware.
7/ Brunswick, Lockatong, and Stockton formations considered as lithofacies, rather than distinct stratigraphic units, by McLaughlin (in Greenman, 1955).
8/ Catskill formation now considered as a continental phase or facies by most geologists familiar with the area. In places it includes equivalents of the Portage group and the Mahantango formation (table 6.)
9/ Locally called Poxono Island shale (of White, 1882).
10/ Martinsburg shale has been called a formation or a group by some geologists working in the area (table 6).

Table 6. Inferred correlation of stratigraphic units of Paleozoic age in Appalachian Highlands portion of

SYSTEM	SERIES	PIEDMONT PROVINCE		NEW ENGLAND PROVINCE		VALLEY AND RIDGE PROVINCE		
		Southern	Northern	Pennsylvania	New Jersey	Pennsylvania	New Jersey	New York
PENNSYLVANIAN						Allegheny formation		
						Pottsville formation		
MISSISSIPPIAN						Mauch Chunk formation		
						Pocono formation		
DEVONIAN	Upper Devonian				Skunnemunk conglomerate	Catskill formation		
						Portage group		
	Middle Devonian				Bellvale sandstone of Lewis and Kümmel (1915)	Hamilton group: Mahantango fm. of Willard (1935)		
					Cornwall shale	Hamilton group: Marcellus shale	Marcellus shale	Marcellus shale
					Kanouse sandstone	Onondaga limestone	Onondaga limestone	Onondaga limestone
								Schoharie grit
	Lower Devonian					Esopus shale	Esopus shale	Esopus shale
						Oriskany sandstone	Oriskany sandstone	Oriskany sandstone
						Helderberg group: Port Ewen limestone Becraft limestone New Scotland limestone Stormville sandstone of Weller (1900) Coeymans limestone	Helderberg group: Port Ewen limestone Becraft limestone New Scotland limestone Stormville sandstone of Weller (1900) Coeymans limestone	Helderberg group: Port Ewen limestone Alsen cherty limestone Becraft limestone New Scotland limestone Kalkberg limestone Coeymans limestone
SILURIAN						Manlius limestone	Manlius limestone	Manlius limestone
						Rondout limestone	Rondout limestone	Rondout limestone
					Decker limestone	Decker limestone	Decker limestone	Decker limestone
						Bossardsville limestone	Bossardsville limestone	
						Wills Creek shale 10)	Wills Creek shale	
					Longwood shale	Bloomsburg red beds	High Falls formation	Bloomsburg red beds Binnewater sandstone (of Grabau, 1906) High Falls shale 4)
					Green Pond conglomerate	Shawangunk conglomerate	Shawangunk conglomerate	Shawangunk conglomerate
ORDOVICIAN	Upper Ordovician	?	? 1) Glenarm Series: Peters Creek schist	Martinsburg shale	Martinsburg shale	Martinsburg shale	Martinsburg shale	
	Middle Ordovician	Wissahickon formation	Glenarm Series: Wissahickon formation			Leesport limestone		
				Jacksonburg limestone	Jacksonburg limestone	Jacksonburg limestone	Jacksonburg limestone	
	Lower Ordovician		Conestoga limestone 2)	Beekmantown limestone		Beekmantown limestone		
			Beekmantown limestone					
	Upper	1) ...ries	Conococheague limestone					

TABLE 6

in Appalachian Highlands portion of Delaware River basin and adjacent areas of New Jersey and New Yor

VALLEY AND RIDGE PROVINCE			APPALACHIAN PLATEAUS PROVINCE		EASTERN PENNSYLVANIA	
nnsylvania	New Jersey	New York	Pennsylvania	New York	Willard, Swartz, and Cleaves (1939); Swartz and Swartz (1939, 1941); Howell, Roberts, and Willard (1950); Trexler (1953). 7)	Pennsylvania Topographic and Geologic Survey 8)
heny formation						Post Pottsville formations
ille formation						Pottsville group
Chunk formation						Mauch Chunk formation
no formation			Pocono formation			Pocono formation
ll formation			Catskill formation	Montrose red shale of White (1881) 9) Catawissa reds of Chadwick (1932) Kattel shale of Chadwick (1932) Oneonta sandstone Onteora formation	Catskill continental phase {Mount Pleasant red shale Elk Mountain gray sandstone Cherry Ridge red beds Honesdale gray sandstone Damascus and Shohola red and gray shale Delaware red flags Analomink red shale	Catskill formation
ge group				Gilboa formation Kaaterskill formation of Willard (1936)	Portage group {Trimmers Rock sandstone Laurens sandstone at base	"Upper Devonian marine"
{Mahantango fm. of Willard (1935)				Kiskatom formation	Hamilton group {Moscow shale Ludlowville formation Centerfield reef Skaneateles formation Marcellus shale	Hamilton group {Mahantango formation Marcellus formation
{Marcellus shale	Marcellus shale	Marcellus shale				
daga limestone	Onondaga limestone	Onondaga limestone			Onondaga group {Buttermilk Falls limestone	Onandaga group
		Schoharie grit			Schoharie shale	
us shale	Esopus shale	Esopus shale			Oriskany group {Esopus shale	
ny sandstone	Oriskany sandstone	Oriskany sandstone			Ridgeley limestone	Oriskany group
rt Ewen limestone Becraft limestone New Scotland limestone Stormville sandstone of Weller (1900) Coeymans limestone	Helderberg group {Port Ewen limestone Becraft limestone New Scotland limestone Stormville sandstone of Weller (1900) Coeymans limestone	Helderberg group {Port Ewen limestone Alsen cherty limestone Becraft limestone New Scotland limestone Kalkberg limestone Coeymans limestone			Helderberg group {Port Ewen shale Becraft limestone New Scotland limestone Kalkberg member in lower part Coeymans limestone	Helderberg group
s limestone	Manlius limestone	Manlius limestone			Manlius limestone	Manlius limestone 5)
t limestone	Rondout limestone	Rondout limestone			Rondout limestone	Rondout limestone 5)
er limestone	Decker limestone	Decker limestone			Decker sandstone	Decker formation 5)
dsville limestone	Bossardsville limestone				Bossardsville limestone	Bossardsville limestone 5)
ek shale 10)	Wills Creek shale				Poxono Island shale	Poxono Island shale 5)
burg red beds	High Falls formation	Bloomsburg red beds Binnewater sandstone (of Grabau, 1906) High Falls shale 4)			Bloomsburg red beds	Bloomsburg formation
unk conglomerate	Shawangunk conglomerate	Shawangunk conglomerate			Shawangunk formation	Shawangunk formation
sburg shale	Martinsburg shale				Martinsburg group {Shochary sandstone Dauphin slate and shale	Martinsburg formation
t limestone						
nburg limestone	Jacksonburg limestone				Jacksonburg limestone	Jacksonburg formation
antown limestone					Beckmantown limestone	Beckmantown formation
wn limestone					Allentown limestone	Allentown formation

System	Series							
DEVONIAN						Portage group		
	Middle Devonian				Bellvale sandstone of Lewis and Kummel (1915)	Hamilton group {Mahantango fm. of Willard (1935)		
					Cornwall shale	Hamilton group {Marcellus shale	Marcellus shale	Marcellus shale
					Kanouse sandstone	Onondaga limestone	Onondaga limestone	Onondaga limestone
	Lower Devonian							Schoharie grit
						Esopus shale	Esopus shale	Esopus shale
						Oriskany sandstone	Oriskany sandstone	Oriskany sandstone
						Helderberg group {Port Ewen limestone Becraft limestone New Scotland limestone Stormville sandstone of Weller (1900) Coeymans limestone	Helderberg group {Port Ewen limestone Becraft limestone New Scotland limestone Stormville sandstone of Weller (1900) Coeymans limestone	Helderberg group {Port Ewen limestone Alsen cherty limestone Becraft limestone New Scotland limestone Kalkberg limestone Coeymans limestone
						Manlius limestone	Manlius limestone	Manlius limestone
						Rondout limestone	Rondout limestone	Rondout limestone
SILURIAN					Decker limestone	Decker limestone	Decker limestone	Decker limestone
						Bossardsville limestone	Bossardsville limestone	
						Wills Creek shale 10)	Wills Creek shale	
					Longwood shale	Bloomsburg red beds	High Falls formation	Bloomsburg red beds Binnewater sandstone (of Grabau, 1906) High Falls shale
					Green Pond conglomerate	Shawangunk conglomerate	Shawangunk conglomerate	Shawangunk conglomerate
		?	?					
ORDOVICIAN	Upper Ordovician	Glenarm series 1) {Wissahickon formation	Glenarm Series 1) {Peters Creek schist	Martinsburg shale	Martinsburg shale	Martinsburg shale	Martinsburg shale	
	Middle Ordovician		Wissahickon formation			Leesport limestone		
				Jacksonburg limestone	Jacksonburg limestone	Jacksonburg limestone	Jacksonburg limestone	
	Lower Ordovician		Conestoga limestone 2) Beekmantown limestone	Beekmantown limestone		Beekmantown limestone		
CAMBRIAN	Upper Cambrian	Cockeysville marble	Conococheague limestone	Allentown limestone of Wherry (1909)	Kittatinny limestone 3)	Allentown limestone of Wherry (1909) Limeport limestone of Howell, Roberts, and Willard (1950)	Kittatinny limestone 3)	
	Middle Cambrian		Elbrook limestone					
			Ledger dolomite			Leithsville formation		
			Kinzers formation	Tomstown dolomite		Tomstown dolomite		
			Vintage dolomite					
	Lower Cambrian		Antietam sandstone					
			Harpers schist					
		Setters formation		Hardyston quartzite	Hardyston quartzite			
			Chickies quartzite (incl. Hellam conglomerate member)					

1) Although previously assigned to the Precambrian, increasing evidence indicates that the Glenarm series is probably lower Paleozoic. Locally the Glenarm series contains a considerable amount of granitic to gabbroic rock.

2) The Conestoga limestone overlaps several formations and unconformably overlies formations as old as the Harpers schist.

3) The Kittatinny limestone in New Jersey includes all carbonate rocks below the Jacksonburg limestone and above the Hardyston quartzite.

4) Classification based on an unpublished report by Carlyle Gray, Pennsylvania Topographic and Geologic Survey.

5) Mappability of these formations in eastern Pennsylvania not tested.

6) Equivalent to Chickies quartz[ite] possibly also to the Antietam sa[ndstone] Harpers schist

7) Classification furnished by B[…]

8) Classification furnished by Ca[…]

9) Renamed Damascus red shale by W[…]

10) Locally called Poxono Island shale ([…]

M

…mation			Catskill formation	Chadwick (1932) Kattel shale of Chadwick (1932) Oneonta sandstone Onteora formation Gilboa formation Kaaterskill formation of Willard (1936) Kiskatom formation	Catskill continental group: Shohola red and gray shale Delaware red flags Analomink red shale	Catskill formation
…oup					Portage group: Trimmers Rock sandstone Laurens sandstone at base	"Upper Devonian marine"
…tango fm. …illard (1935)					Hamilton group: Moscow shale Ludlowville formation Centerfield reef Skaneateles formation	Hamilton group: Mahantango formation
…ellus shale	Marcellus shale	Marcellus shale			Marcellus shale	Marcellus formation
…limestone	Onondaga limestone	Onondaga limestone			Onondaga group: Buttermilk Falls limestone	Onondaga group
		Schoharie grit			Schoharie shale	
…hale	Esopus shale	Esopus shale			Esopus shale	
…ndstone	Oriskany sandstone	Oriskany sandstone			Oriskany group: Ridgeley limestone	Oriskany group
…limestone	Helderberg group: Port Ewen limestone	Helderberg group: Port Ewen limestone Alsen cherty limestone			Helderberg group: Port Ewen shale	Helderberg group
…t limestone	Becraft limestone	Becraft limestone			Becraft limestone	
…land limestone	New Scotland limestone	New Scotland limestone			New Scotland limestone	
…le sandstone …r (1900)	Stormville sandstone of Weller (1900)	Kalkberg limestone			Kalkberg member in lower part	
…ns limestone	Coeymans limestone	Coeymans limestone			Coeymans limestone	
…nestone	Manlius limestone	Manlius limestone			Manlius limestone	Manlius limestone 5)
…estone	Rondout limestone	Rondout limestone			Rondout limestone	Rondout limestone 5)
…estone	Decker limestone	Decker limestone			Decker sandstone	Decker formation 5)
… limestone	Bossardsville limestone				Bossardsville limestone	Bossardsville limestone 5)
…ale 10)	Wills Creek shale				Poxono Island shale	Poxono Island shale 5)
…ed beds	High Falls formation	Bloomsburg red beds Binnewater sandstone (of Grabau, 1906) High Falls shale 4)			Bloomsburg red beds	Bloomsburg formation
…onglomerate	Shawangunk conglomerate	Shawangunk conglomerate			Shawangunk formation	Shawangunk formation
…shale	Martinsburg shale				Martinsburg group: Shochary sandstone Dauphin slate and shale	Martinsburg formation
…nestone						
…g limestone	Jacksonburg limestone				Jacksonburg limestone	Jacksonburg formation
…n limestone					Beekmantown limestone	Beekmantown formation
…nestone …(1909) …limestone …, Roberts, …rd (1950)	Kittatinny limestone 3)				Allentown limestone Limeport limestone	Allentown formation
						(Middle Cambrian, not proved present)
…formation					Leithsville formation	
…dolomite						Tomstown group: Ledger dolomite Kinzers formation Vintage dolomite
					Hardyston formation	Hardyston formation 6)

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6) Equivalent to Chickies quartzite and possibly also to the Antietam sandstone and Harpers schist
7) Classification furnished by Bradford Willard, personal communication (1958)
8) Classification furnished by Carlyle Gray, personal communication (1958)
9) Renamed Damascus red shale by Willard (1936)
10) Locally called Poxono Island shale (of White, 1882)

Table 9.--Representative chemical analyses of water in unconsolidated sediments in Appalachian Highlands

(Concentrations in parts per million)

Analysis no.	County and state	Depth (feet)	Date of collection	Temperature °F	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)
1	Monroe, Pa.	--	9-22-30	48	--	--	--	2	--	- - - 1 - - -		16	< 2
2	Wayne, Pa.	28	9-20-30	60	--	--	--	7	--	- - - 1 - - -		25	14
3	Orange, N. Y.	110	8-7-47	--	--	.18	0.01	--	--	--	--	133	10.1
4	Sullivan, N. Y.	57	4-19-56	--	--	.10	--	--	--	--	--	33	--
5	Delaware, N. Y.	166	7-10-46	--	--	.15	.015	--	--	--	--	15	8.9
6	Delaware, N. Y.	70	5-18-49	--	8.5	.15	--	16	2.8	- - - 5.7 - - -		52	4.1

Table 10.--Representative chemical analyses of water in consolidated rocks in Appalachian Highlands

(Concentrations in parts per million)

Analysis no.	County and state	Depth (feet)	Date of collection	Temperature °F	Silica (SiO_2)	Iron (Fe)	Manganese (mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)
								Martinsburg	shale				
1	Lehigh, Pa.	75	11-18-54	54	--	1.4	--	--	--	- - 4.3 - - -		62	61
2	Lehigh, Pa.	129	11-4-54	54	--	.33	--	--	--	- - 3.6 - - -		54	34
								Catskill	formation				
3	Schuylkill, Pa.	120	5-4-49	49	7.5	.17	--	5.0	3.8	1.9	.7	8	12
4	Wayne, Pa.	238	9-19-30	52	13	.01	--	28	4.8	20	2.4	104	23
								Lockatong	formation				
5	Bucks, Pa.	330	4-22-53	53	14	.04	--	28	15	7.0	.6	120	38
6	Bucks, Pa.	--	4-16-53	53	13	.29	--	50	15	15	1.2	174	54
								Stockton	formation				
7	Chester, Pa.	752	6-7-56	--	26	.14	0.01	45	24	- - 17 - - -		127	123
8	Montgomery, Pa.	--	6-28-56	--	30	.17	.00	59	17	- - 17 - - -		154	47
9	Bucks, Pa.	--	3-24-53	54	18	.66	--	29	17	8.3	.8	154	19
10	Bucks, Pa.	--	4-17-53	54	15	.04	--	30	9.9	37	3.5	48	72
11	Bucks, Pa.	227	4-9-53	53	20	.25	--	22	6.7	12	1	72	34
12	Mercer, N. J.	372	9-27-49	--	27	.03	--	27	6.8	12	1.7	88	20
								Brunswick	formation				
13	Montgomery, Pa.	100	4-21-49	54	20	.17	--	52	13	11	1.4	198	23
14	Bucks, Pa.	300	3-25-53	52	22	1.3	--	77	18	13	1.0	164	144
15	Bucks, Pa.	303	4-7-53	53	19	1.1	--	37	16	13	1.8	172	31
16	Bucks, Pa.	511	9-8-53	56	17	.04	--	49	14	26	.6	156	53
								Carbonate	rocks				
17	Lancaster, Pa.	105	9-24-25		7.9	.10	--	72	9.4	11	7.1	217	30
18	Bucks, Pa.		4-14-53	54	7.2	.08	--	65	36	18	2.2	312	15
19	Lehigh, Pa.	175	5-15-53	58	9.8	.01	--	--	--	- - 6.5 - - -		134	2.3
20	Lehigh, Pa.	100	5-12-53	52	6.0	.02	--	--	--	- - 3.5 - - -		108	8.4
21	Lehigh, Pa.	34	1-6-55	50		.63	--	--	--	- - 4.2 - - -		258	92
								Diabase					
22	Montgomery, Pa.	350	4-21-49	--	31	1.0	--	22	9.6	6.1	.9	78	25
23	Bucks, Pa.	765	4-8-53	55	25	.4	--	94	9.1	4.4	1.0	126	169
24	Bucks, Pa.	70	4-20-53	52	18	1.4	--	48	15	11	2.3	196	34
								Gneiss					
25	Chester, Pa.	84	9-25-25	--	31	.31	--	4.7	2.3	4.3	.9	30	3.7
26	Bucks, Pa.	226	9-7-53	53	8.7	.29	--	2.9	1.3	5.0	1.3	8	.3
27	Bucks, Pa.	198	4-9-53	54	15	1.1	--	18	7.0	16	3.3	106	9.5
28	Lehigh, Pa.	250	12-2-54	53	--	.61	--	--	--	- - 2.6 - - -		45	5.6
29	Lehigh, Pa.	90	12-7-54	53	--	1.5	--	--	--	- - 2.1 - - -		29	29
								Chickies	quartzite				
30	Chester, Pa.	80	10-1-25	53	7.6	0.14	--	4.6	3.9	6.2	1.4	5.4	4.2
31	Bucks, Pa.	504	9-7-53	53	17	1.6	--	25	5.1	4.5	3.8	80	1[illegible]

...epresentative chemical analyses of water in unconsolidated sediments in Appalachian Highlands

(Concentrations in parts per million)

...on	Temperature °F	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Hardness as $CaCO_3$ Total	Hardness as $CaCO_3$ Non carbonate	pH
	48	--	--	--	2	--	--- 1 ---		16	< 2	1.0	--	0.1	18	14	--	--
	60	--	--	--	7	--	--- 1 ---		25	14	4.0	--	2.4	50	40	--	--
	--	--	.18	0.01	--	--	--	--	133	10.1	2.4	--	--	144	88	--	7.9
	--	--	.10	--	--	--	--	--	33	--	7.8	--	1.8	--	58	--	6.0
	--	--	.15	.015	--	--	--	--	15	8.9	.8	--	--	33	28	--	6.8
	--	8.5	.15	--	16	2.8	--- 5.7 ---		52	4.1	4.5	0.0	13	94	51	9	7.9

...able 10.--Representative chemical analyses of water in consolidated rocks in Appalachian Highlands

(Concentrations in parts per million)

...ion	Temperature °F	Silica (SiO_2)	Iron (Fe)	Manganese (mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Hardness as $CaCO_3$ Total	Hardness as $CaCO_3$ Non-carbonate	pH
					Martinsburg	shale											
	54	--	1.4	--	--	--	-- 4.3 ---		62	61	7	--	7.8	--	121	70	7.7
	54	--	.33	--	--	--	-- 3.6 ---		54	34	5	--	15	--	91	47	6.8
					Catskill	formation											
	49	7.5	.17	--	5.0	3.8	1.9	.7	8	12	3.5	0	12	53	28	22	6.2
	52	13	.01	--	28	4.8	20	2.4	104	23	20	--	3.0	176	90	4	--
					Lockatong	formation											
	53	14	.04	--	28	15	7.0	.6	120	38	7.0	0.0	2.1	229	132	33	7.4
	53	13	.29	--	50	15	15	1.2	174	54	16	.1	.1	274	186	44	7.5
					Stockton	formation											
	--	26	.14	0.01	45	24	-- 17 ---		127	123	9.5	.1	2.7	346	211	107	8.1
	--	30	.17	.00	59	17	-- 17 ---		154	47	28.	.1	48	351	217	91	7.2
	54	18	.66	--	29	17	8.3	.8	154	19	8.5	.0	5.5	195	142	16	7.7
	54	15	.04	--	30	9.9	37	3.5	48	72	54	.0	16	304	116	76	6.0
	53	20	.25	--	22	6.7	12	1	72	34	10	.0	1.2	156	82	23	6.3
	--	27	.03	--	27	6.8	12	1.7	88	20	11	.0	12	158	95	28	6.7
					Brunswick	formation											
	54	20	.17	--	52	13	11	1.4	198	23	7.0	.0	12	242	183	21	7.5
	52	22	1.3	--	77	18	13	1.0	164	144	7.0	.3	2.8	381	266	132	7.7
	53	19	1.1	--	37	16	13	1.8	172	31	10	.1	1.8	217	158	17	7.4
	56	17	.04	--	49	14	26	.6	156	53	22	.1	21	311	180	52	7.7
					Carbonate	rocks											
		7.9	.10	--	72	9.4	11	7.1	217	30	22	--	1.0	290	219	40	--
	54	7.2	.08	--	65	36	18	2.2	312	15	46	--	22	397	310	55	7.0
	58	9.8	.01	--	--	--	-- 6.5 ---		134	2.3	4.0	--	.3	--	104	0	7.8
	52	6.0	.02	--	--	--	-- 3.5 ---		108	8.4	4.5	--	10	--	104	16	7.7
	50		.63	--	--	--	-- 4.2 ---		258	92	7	--	15	--	320	109	7.4
					Diabase												
	--	31	1.0	--	22	9.6	6.1	.9	78	25	12	.1	.2	144	94	31	7.2
	55	25	.4	--	94	9.1	4.4	1.0	126	169	2.2	.1	.3	398	272	169	7.5
	52	18	1.4	--	48	15	11	2.3	196	34	8.5	.1	3.7	247	181	21	7.3
					Gneiss												
	--	31	.31	--	4.7	2.3	4.3	.9	30	3.7	2.1	--	1.5	67	21	0	--
	53	8.7	.29	--	2.9	1.3	5.0	1.3	8	.3	7.0	0.0	7.9	51	13	6	5.4
	54	15	1.1	--	18	7.0	16	3.3	106	9.5	8.0	.1	5.8	138	74	0	6.8
	53	--	.61	--	--	--	-- 2.6 ---		45	5.6	1	--	3.1	--	41	4	7.9
	53	--	1.5	--	--	--	-- 2.1 ---		29	29	1	--	14	--	62	38	6.6
					Chickies	quartzite											
	53	7.6	0.14	--	4.6	3.9	6.2	1.4	5.4	4.2	10	—	25	64	27	22	--
	53	17	1.6	--	25	5.1	4.5	3.8	80	18	8.0	.4	.3	122	83	18	7.1
					Wissahickon	formation											

no.		(feet)		°F	(SiO_2)	(Fe)	(Mn)	(Ca)	(Mg)	(Na)	(K)		
1	Monroe, Pa.	--	9-22-30	48	--	--	--	2	--	1		16	< 2
2	Wayne, Pa.	28	9-20-30	60	--	--	--	7	--	1		25	14
3	Orange, N. Y.	110	8-7-47	--	--	.18	0.01	--	--	--	--	133	10.1
4	Sullivan, N. Y.	57	4-19-56	--	--	.10	--	--	--	--	--	33	--
5	Delaware, N. Y.	166	7-10-46	--	--	.15	.015	--	--	--	--	15	8.9
6	Delaware, N. Y.	70	5-18-49	--	8.5	.15	--	16	2.8	5.7		52	4.1

Table 10.--Representative chemical analyses of water in consolidated rocks in Appalachian Highlands

(Concentrations in parts per million)

Analysis no.	County and state	Depth (feet)	Date of collection	Temperature °F	Silica (SiO_2)	Iron (Fe)	Manganese (mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)
								Martinsburg	shale				
1	Lehigh, Pa.	75	11-18-54	54	--	1.4	--	--	--	4.3		62	61
2	Lehigh, Pa.	129	11-4-54	54	--	.33	--	--	--	3.6		54	34
								Catskill	formation				
3	Schuylkill, Pa.	120	5-4-49	49	7.5	.17	--	5.0	3.8	1.9	.7	8	12
4	Wayne, Pa.	238	9-19-30	52	13	.01	--	28	4.8	20	2.4	104	23
								Lockatong	formation				
5	Bucks, Pa.	330	4-22-53	53	14	.04	--	28	15	7.0	.6	120	38
6	Bucks, Pa.	--	4-16-53	53	13	.29	--	50	15	15	1.2	174	54
								Stockton	formation				
7	Chester, Pa.	752	6-7-56	--	26	.14	0.01	45	24	17		127	123
8	Montgomery, Pa.	--	6-28-56	--	30	.17	.00	59	17	17		154	47
9	Bucks, Pa.	--	3-24-53	54	18	.66	--	29	17	8.3	.8	154	19
10	Bucks, Pa.	--	4-17-53	54	15	.04	--	30	9.9	37	3.5	48	72
11	Bucks, Pa.	227	4-9-53	53	20	.25	--	22	6.7	12	1	72	34
12	Mercer, N. J.	372	9-27-49	--	27	.03	--	27	6.8	12	1.7	88	20
								Brunswick	formation				
13	Montgomery, Pa.	100	4-21-49	54	20	.17	--	52	13	11	1.4	198	23
14	Bucks, Pa.	300	3-25-53	52	22	1.3	--	77	18	13	1.0	164	144
15	Bucks, Pa.	303	4-7-53	53	19	1.1	--	37	16	13	1.8	172	31
16	Bucks, Pa.	511	9-8-53	56	17	.04	--	49	14	26	.6	156	53
								Carbonate	rocks				
17	Lancaster, Pa.	105	9-24-25		7.9	.10	--	72	9.4	11	7.1	217	30
18	Bucks, Pa.		4-14-53	54	7.2	.08	--	65	36	18	2.2	312	15
19	Lehigh, Pa.	175	5-15-53	58	9.8	.01	--	--	--	6.5		134	2.3
20	Lehigh, Pa.	100	5-12-53	52	6.0	.02	--	--	--	3.5		108	8.4
21	Lehigh, Pa.	34	1-6-55	50		.63	--	--	--	4.2		258	92
								Diabase					
22	Montgomery, Pa.	350	4-21-49	--	31	1.0	--	22	9.6	6.1	.9	78	25
23	Bucks, Pa.	765	4-8-53	55	25	.4	--	94	9.1	4.4	1.0	126	169
24	Bucks, Pa.	70	4-20-53	52	18	1.4	--	48	15	11	2.3	196	34
								Gneiss					
25	Chester, Pa.	84	9-25-25	--	31	.31	--	4.7	2.3	4.3	.9	30	3.7
26	Bucks, Pa.	226	9-7-53	53	8.7	.29	--	2.9	1.3	5.0	1.3	8	.3
27	Bucks, Pa.	198	4-9-53	54	15	1.1	--	18	7.0	16	3.3	106	9.5
28	Lehigh, Pa.	250	12-2-54	53	--	.61	--	--	--	2.6		45	5.6
29	Lehigh, Pa.	90	12-7-54	53	--	1.5	--	--	--	2.1		29	29
								Chickies	quartzite				
30	Chester, Pa.	80	10-1-25	53	7.6	0.14	--	4.6	3.9	6.2	1.4	5.4	4.2
31	Bucks, Pa.	504	9-7-53	53	17	1.6	--	25	5.1	4.5	3.8	80	[illegible]
								Wissahickon	formation				
32	New Castle, Del.	110	1-19-56	51	18	.04	--	11	4.0	5.6		35	11
33	Chester, Pa.	184	9-21-25	--	23	.11	--	5.4	4.6	3.7	1.6	22	5.0
34	Delaware, Pa.	48	9-26-25	54	28	4.1	--	11	4.2	5.8	1.4	43	4.3
35	Bucks, Pa.	300	4-28-53	57	24	3.4	--	4.1	1.7	8.3	2.4	26	9.1
36	Bucks, Pa.	90	1-21-54	58	20	.15	--	14	8.3	7.4	2.8	26	18

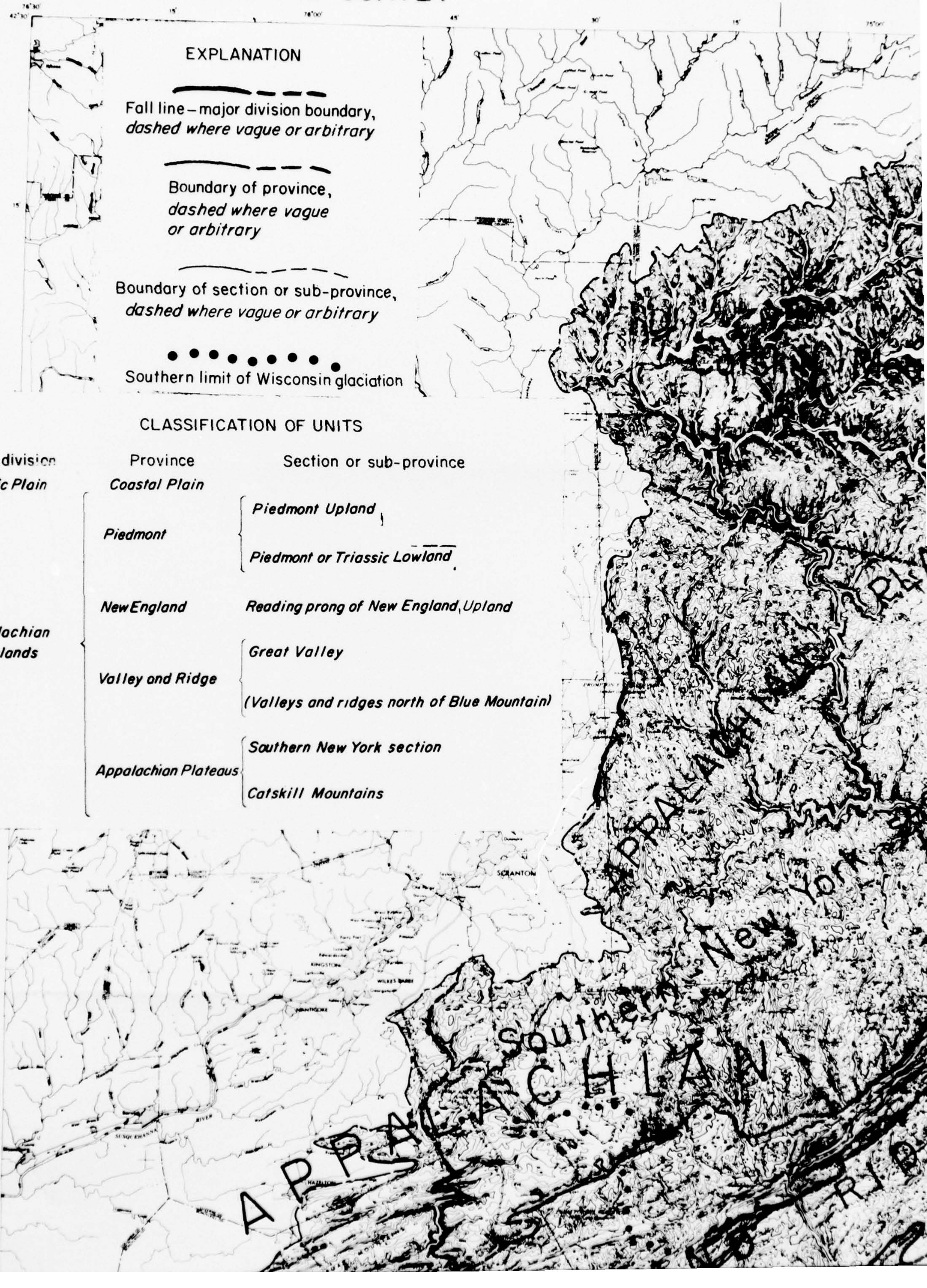
...ion	...ature °F	(SiO_2)	(Fe)	...ganese (Mn)	...cium (Ca)	...sium (Mg)	(Na)	...sium (K)	...bonate (HCO_3)	(SO_4)	...ide (Cl)	...ide (F)	...trate (NO_3)	...solids	...	... car-bonate	pH
0	48	--	--	--	2	--	1		16	< 2	1.0	--	0.1	18	14	--	--
0	60	--	--	--	7	--	1		25	14	4.0	--	2.4	50	40	--	--
	--	--	.18	0.01	--	--	--	--	133	10.1	2.4	--	--	144	88	--	7.9
6	--	--	.10	--	--	--	--	--	33	--	7.8	--	1.8	--	58	--	6.0
6	--	--	.15	.015	--	--	--	--	15	8.9	.8	--	--	33	28	--	6.8
9	--	8.5	.15	--	16	2.8	5.7		52	4.1	4.5	0.0	13	94	51	9	7.9

Table 10.--**Representative chemical analyses of water in consolidated rocks in Appalachian Highlands**

(Concentrations in parts per million)

...f ...tion	Temperature °F	Silica (SiO_2)	Iron (Fe)	Manganese (mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Hardness as $CaCO_3$ Total	Hardness as $CaCO_3$ Non-carbonate	pH
Martinsburg shale																	
-54	54	--	1.4	--	--	--	4.3		62	61	7	--	7.8	--	121	70	7.7
54	54	--	.33	--	--	--	3.6		54	34	5	--	15	--	91	47	6.8
Catskill formation																	
9	49	7.5	.17	--	5.0	3.8	1.9	.7	8	12	3.5	0	12	53	28	22	6.2
30	52	13	.01	--	28	4.8	20	2.4	104	23	20	--	3.0	176	90	4	--
Lockatong formation																	
53	53	14	.04	--	28	15	7.0	.6	120	38	7.0	0.0	2.1	229	132	33	7.4
53	53	13	.29	--	50	15	15	1.2	174	54	16	.1	.1	274	186	44	7.5
Stockton formation																	
5	--	26	.14	0.01	45	24	17		127	123	9.5	.1	2.7	346	211	107	8.1
56	--	30	.17	.00	59	17	17		154	47	28.	.1	48	351	217	91	7.2
53	54	18	.66	--	29	17	8.3	.8	154	19	8.5	.0	5.5	195	142	16	7.7
53	54	15	.04	--	30	9.9	37	3.5	48	72	54	.0	16	304	116	76	6.0
3	53	20	.25	--	22	6.7	12	1	72	34	10	.0	1.2	156	82	23	6.3
49	--	27	.03	--	27	6.8	12	1.7	88	20	11	.0	12	158	95	28	6.7
Brunswick formation																	
49	54	20	.17	--	52	13	11	1.4	198	23	7.0	.0	12	242	183	21	7.5
53	52	22	1.3	--	77	18	13	1.0	164	144	7.0	.3	2.8	381	266	132	7.7
3	53	19	1.1	--	37	16	13	1.8	172	31	10	.1	1.8	217	158	17	7.4
3	56	17	.04	--	49	14	26	.6	156	53	22	.1	21	311	180	52	7.7
Carbonate rocks																	
25		7.9	.10	--	72	9.4	11	7.1	217	30	22	--	1.0	290	219	40	--
53	54	7.2	.08	--	65	36	18	2.2	312	15	46	--	22	397	310	55	7.0
53	58	9.8	.01	--	--	--	6.5		134	2.3	4.0	--	.3	--	104	0	7.8
53	52	6.0	.02	--	--	--	3.5		108	8.4	4.5	--	10	--	104	16	7.7
5	50		.63	--	--	--	4.2		258	92	7	--	15	--	320	109	7.4
Diabase																	
49	--	31	1.0	--	22	9.6	6.1	.9	78	25	12	.1	.2	144	94	31	7.2
3	55	25	.4	--	94	9.1	4.4	1.0	126	169	2.2	.1	.3	398	272	169	7.5
53	52	18	1.4	--	48	15	11	2.3	196	34	8.5	.1	3.7	247	181	21	7.3
Gneiss																	
5	--	31	.31	--	4.7	2.3	4.3	.9	30	3.7	2.1	--	1.5	67	21	0	--
	53	8.7	.29	--	2.9	1.3	5.0	1.3	8	.3	7.0	0.0	7.9	51	13	6	5.4
	54	15	1.1	--	18	7.0	16	3.3	106	9.5	8.0	.1	5.8	138	74	0	6.8
4	53	--	.61	--	--	--	2.6		45	5.6	1	--	3.1	--	41	4	7.9
4	53	--	1.5	--	--	--	2.1		29	29	1	--	14	--	62	38	6.6
Chickies quartzite																	
5	53	7.6	0.14	--	4.6	3.9	6.2	1.4	5.4	4.2	10	--	25	64	27	22	--
	53	17	1.6	--	25	5.1	4.5	3.8	80	18	8.0	.4	.3	122	83	18	7.1
Wissahickon formation																	
5	51	18	.04	--	11	4.0	5.6		35	11	7	.0	7.6	87	44	15	6.3
5	--	23	.11	--	5.4	4.6	3.7	1.6	22	5.0	4.0	--	16	74	32	9	--
5	54	28	4.1	--	11	4.2	5.8	1.4	43	4.3	5.2	--	11	85	45	14	--
3	57	24	3.4	--	4.1	1.7	8.3	2.4	26	9.1	5.4	.1	.3	72	17	0	5.9
	58	20	.15	--	14	8.3	7.4	2.8	26	18	16	.1	34	154	69	48	6.9

U. S. GEOLOGICAL SURVEY



EXPLANATION

Fall line – major division boundary, *dashed where vague or arbitrary*

Boundary of province, *dashed where vague or arbitrary*

Boundary of section or sub-province, *dashed where vague or arbitrary*

Southern limit of Wisconsin glaciation

CLASSIFICATION OF UNITS

Major division	Province	Section or sub-province
Atlantic Plain	*Coastal Plain*	
Appalachian Highlands	*Piedmont*	*Piedmont Upland*
		Piedmont or Triassic Lowland
	New England	*Reading prong of New England Upland*
	Valley and Ridge	*Great Valley*
		(Valleys and ridges north of Blue Mountain)
	Appalachian Plateaus	*Southern New York section*
		Catskill Mountains

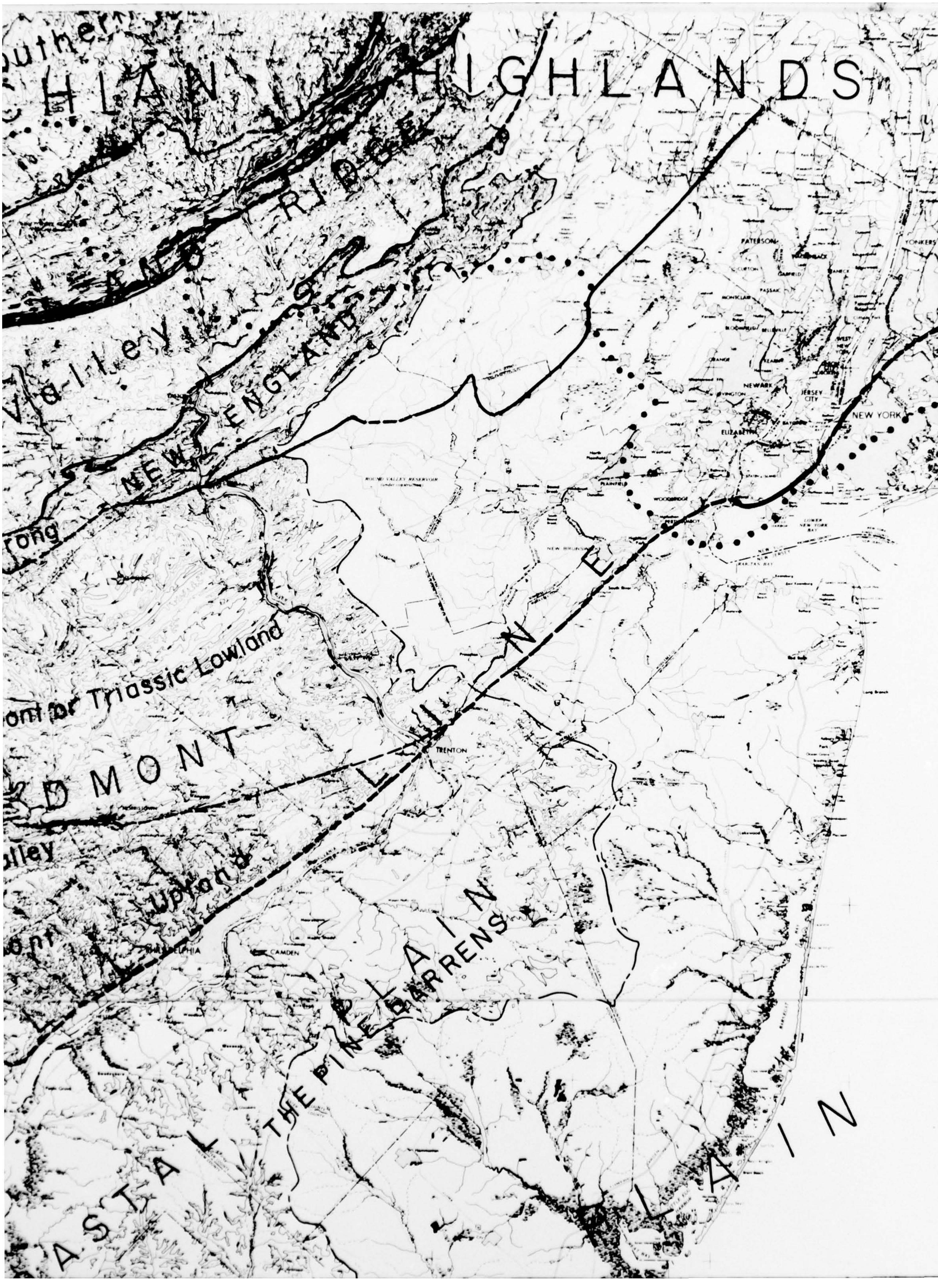
2

PLATE 3

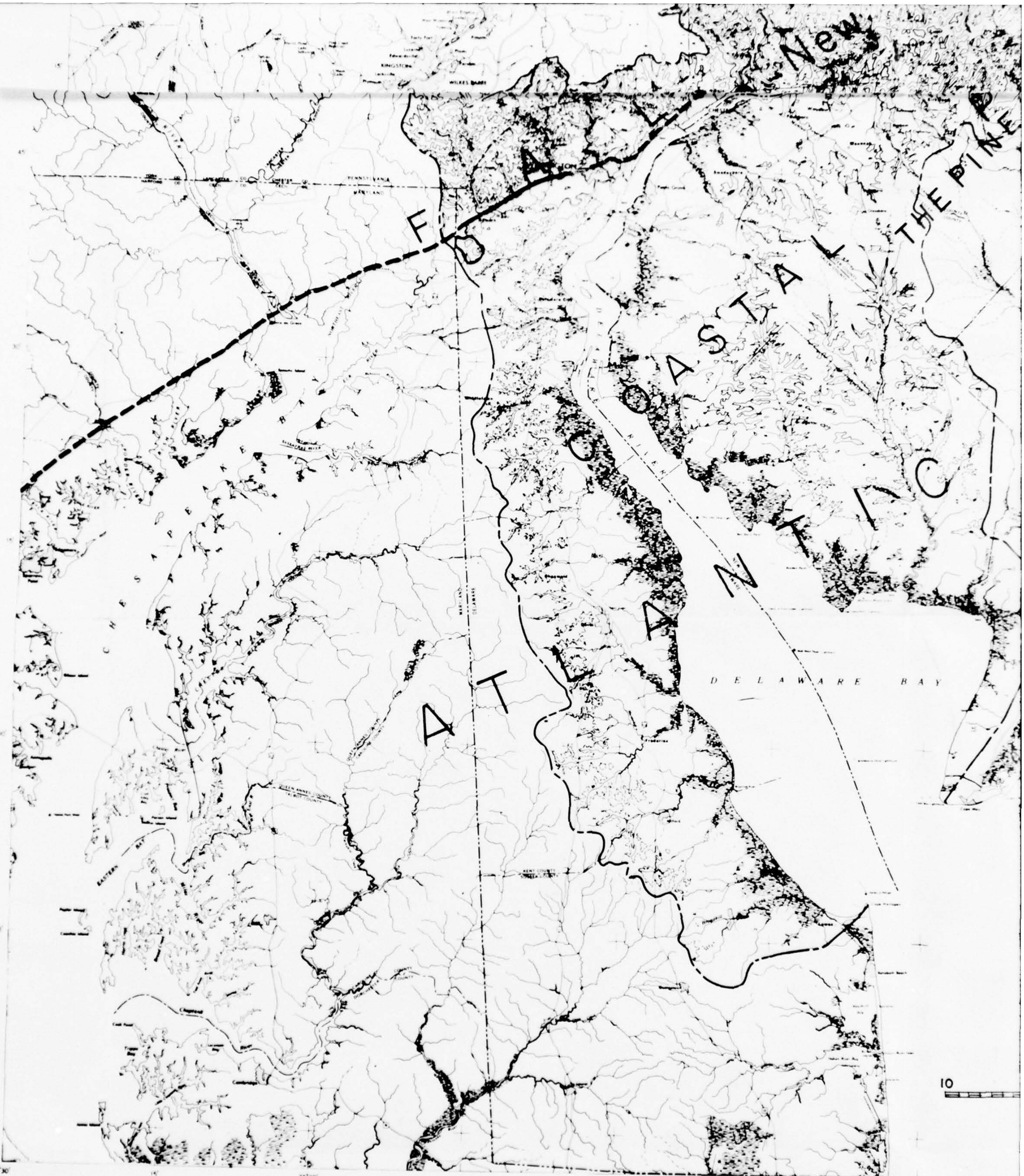
PLATEAUS
New York
HIGHLANDS
RIDGE
MOUNTAINS
PATERSON
YONKERS

3


APPALACHIAN
VALLEY
Great Valley
NEW ENGLAND
Reading prong
Reading prong
Piedmont or Triassic Lowland
PIEDMONT
Chester Valley
Piedmont Upland

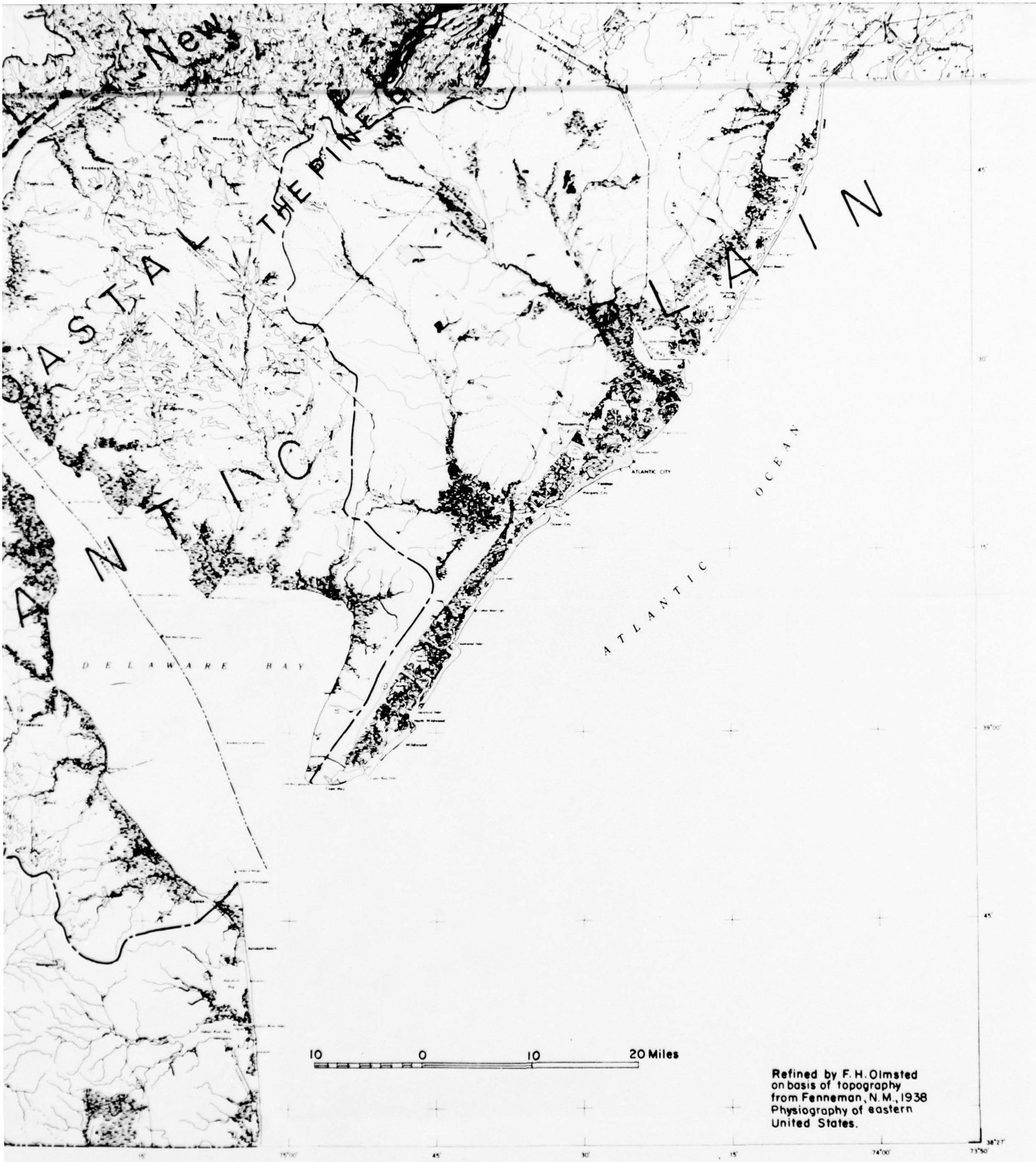

HIGHLANDS
NEW ENGLAND
Valley
Triassic Lowland
Upland
THE PINE BARRENS
PATERSON
YONKERS
CLIFTON
MONTCLAIR
NEWARK
JERSEY CITY
NEW YORK
ELIZABETH
PLAINFIELD
WOODBRIDGE
ROUND VALLEY RESERVOIR
LOWER NEW YORK BAY
TRENTON
CAMDEN

4



MAP OF REGION INCLUDING THE DELAWARE RIVER BAS

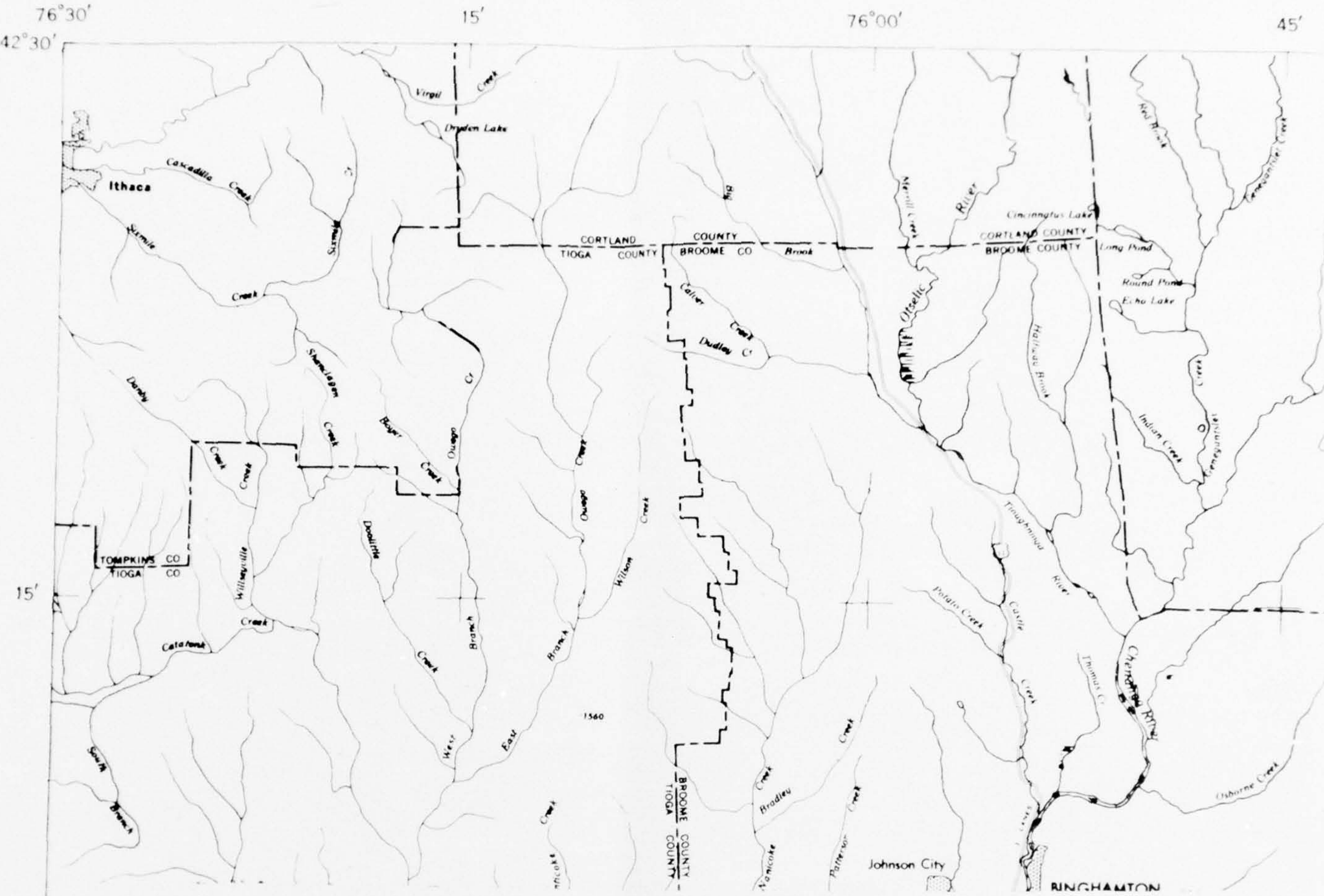
5



DELAWARE RIVER BASIN SHOWING PHYSIOGRAPHIC UNITS

6

U.S. GEOLOGICAL SURVEY



EXPLANATION

Unconsolidated sediments unmapped in area generally south of 41°00' N latitude and west of 75°45' W longitude

42°00'

QUATERNARY

Recent

Qbd — Beach and dune sand

Qms — Marsh and swamp deposits

Qao — Alluvium and glacial outwash, stratified glacial drift of uplands *in northeastern Pennsylvania includes some swamp and marsh deposits*

Pleistocene

Wisconsin stage

Qt — Glacial till *Includes scattered exposures of consolidated rocks*

Qm — Terminal and recessional moraines

Pre-Wisconsin stage

Qed — Early glacial drift

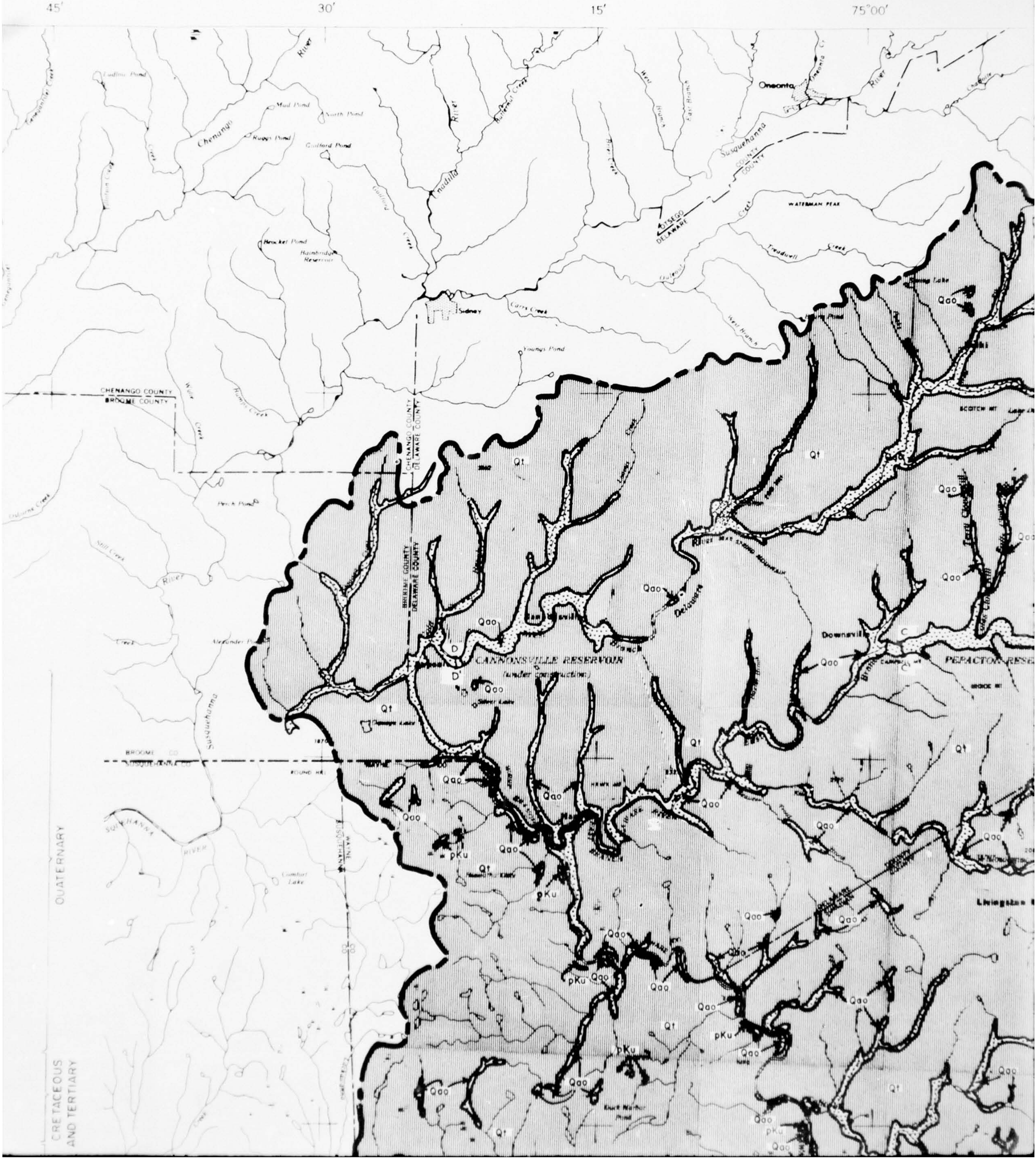
Qpb — Pensauken and Bridgeton formations

CRETACEOUS AND TERTIARY

TKu — Sediments, undifferentiated

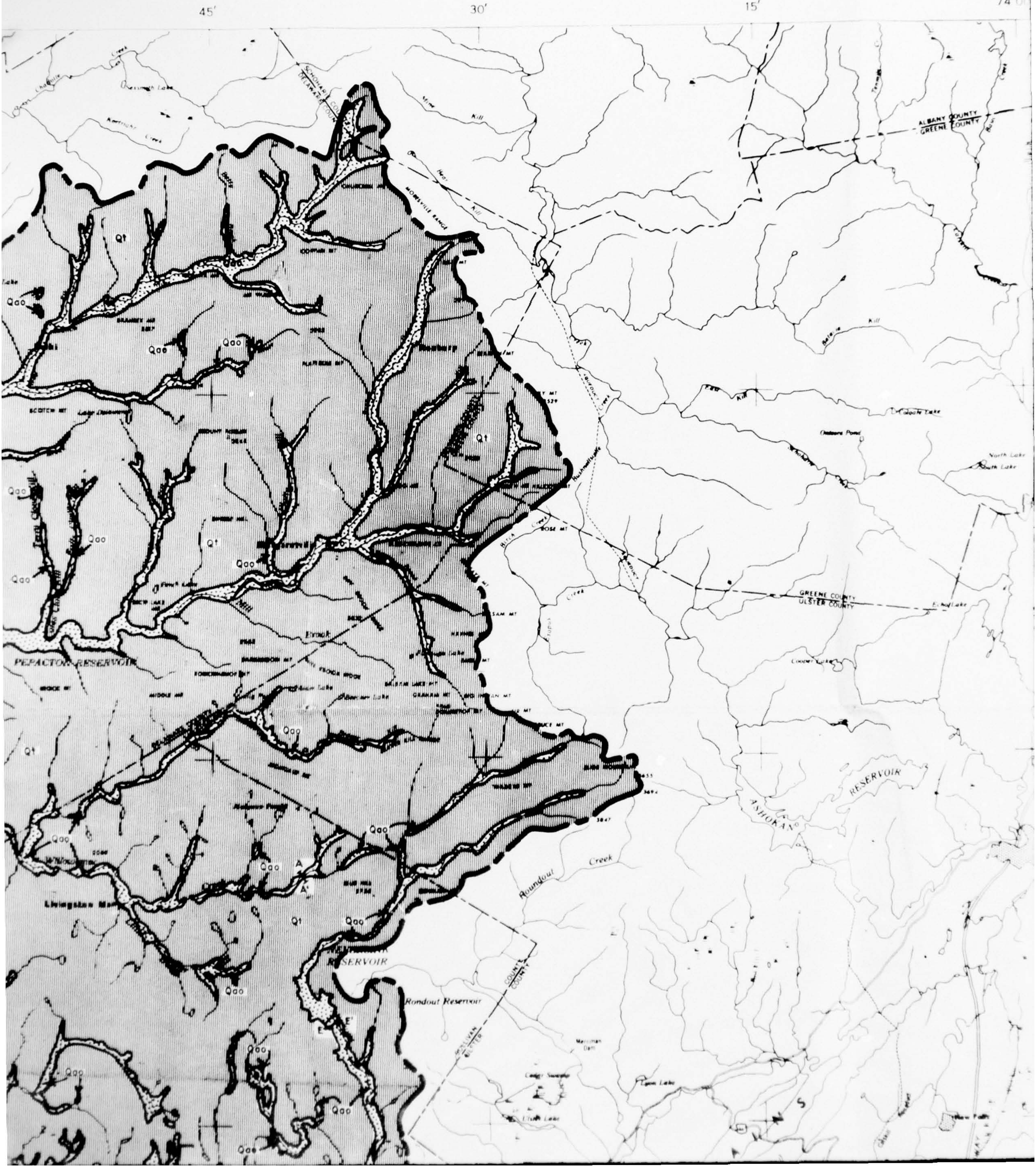
45'

2


45'
30'
15'
75°00'
Chenango
River
Ludlow Pond
Mud Pond
North Pond
Ruggs Pond
Guilford Pond
Brackel Pond
Bainbridge Reservoir
Unadilla
River
Oneonta
Susquehanna
River
OTSEGO COUNTY
DELAWARE COUNTY
WATERMAN PEAK
Treadwell
Creek
Sidney
Carrs Creek
Youngs Pond
West Branch
CHENANGO COUNTY
BROOME COUNTY
CHENANGO COUNTY
DELAWARE COUNTY
BROOME COUNTY
DELAWARE COUNTY
Perch Pond
Osborne Creek
Still Creek
River
Creek
Delaware
CANNONSVILLE RESERVOIR
(under construction)
Downsville
PEPACTON RESER
Qao
Qt
pKu
D
D'
C
C'
BROOME CO
SUSQUEHANNA CO
Susquehanna
SUSQUEHANNA RIVER
Comfort Lake
SUSQUEHANNA
WAYNE
QUATERNARY
CRETACEOUS AND TERTIARY

3

PLATE



45′
30′
15′
74°00′
ALBANY COUNTY
GREENE COUNTY
GREENE COUNTY
ULSTER COUNTY
PEPACTON RESERVOIR
ASHOKAN RESERVOIR
Roundout Creek
Rondout Reservoir
Qt
Qao
North Lake
South Lake
Cooper Lake

4

PLATE 14

30'
15'
74°00'
73°50'
42°30
15'
42°00'
45'
ALBANY COUNTY
GREENE COUNTY
GREENE COUNTY
ULSTER COUNTY
COLUMBIA COUNTY
DUTCHESS COUNTY
Colgate Lake
Onteora Pond
North Lake
South Lake
Echo Lake
Cooper Lake
Catskill
Saugerties
ASHOKAN
RESERVOIR
KINGSTON
Roundout Creek
Rondout Reservoir
RESERVOIR
Qt
Qao
POUGHKEEPSIE

5

Consolidated rocks, undifferentiated

Subdivisions shown on pl. 12. Locally covered by scattered masses of early glacial drift north of southern limit of Jerseyan drift

PRE-CRETACEOUS

Geologic contact

dashed where approximately located

30′

Southern limit of Wisconsin glaciation

Southern limit of Illinoian glaciation

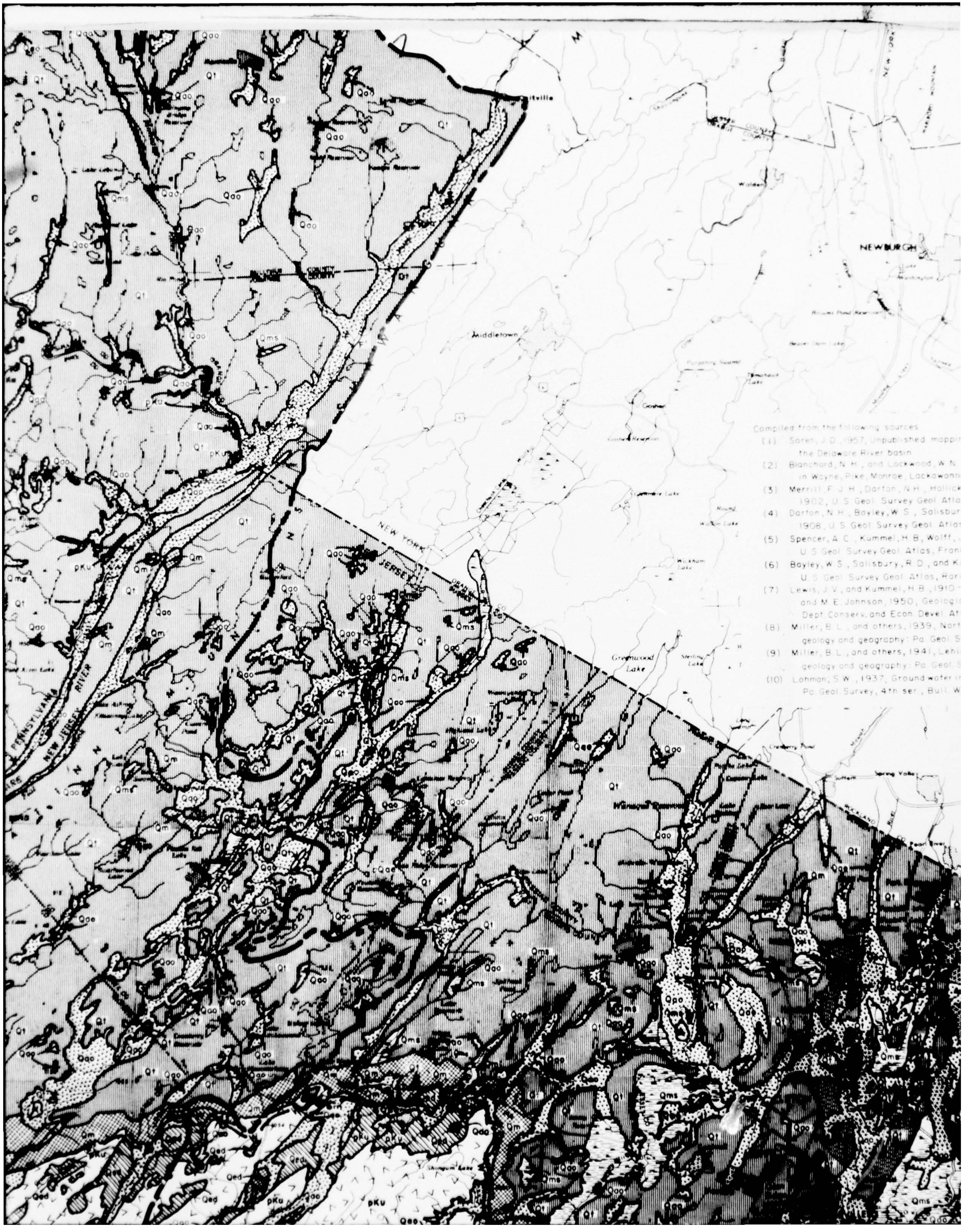
Southern limit of Jerseyan drift

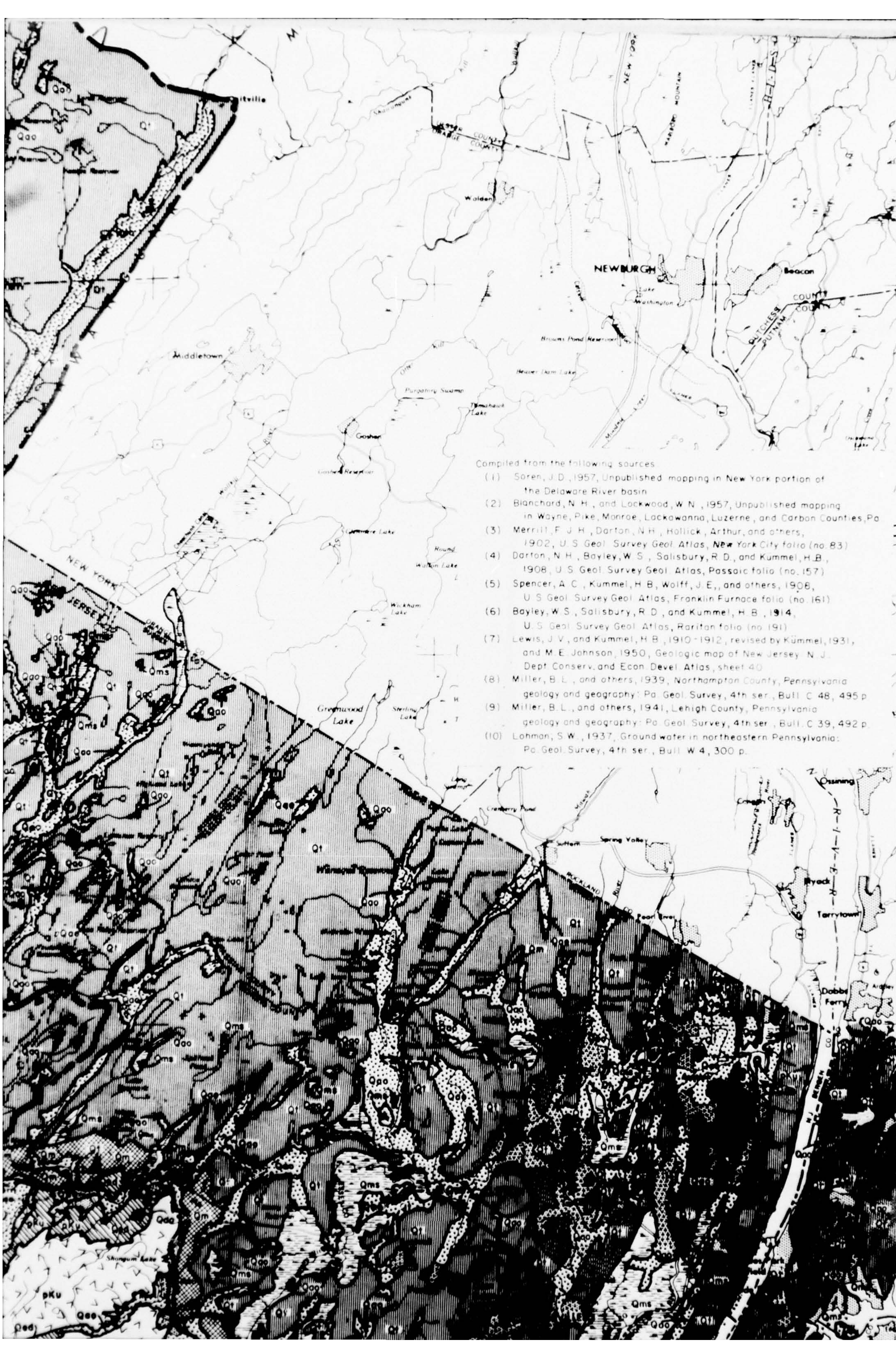
Boundary of Delaware River basin

15′

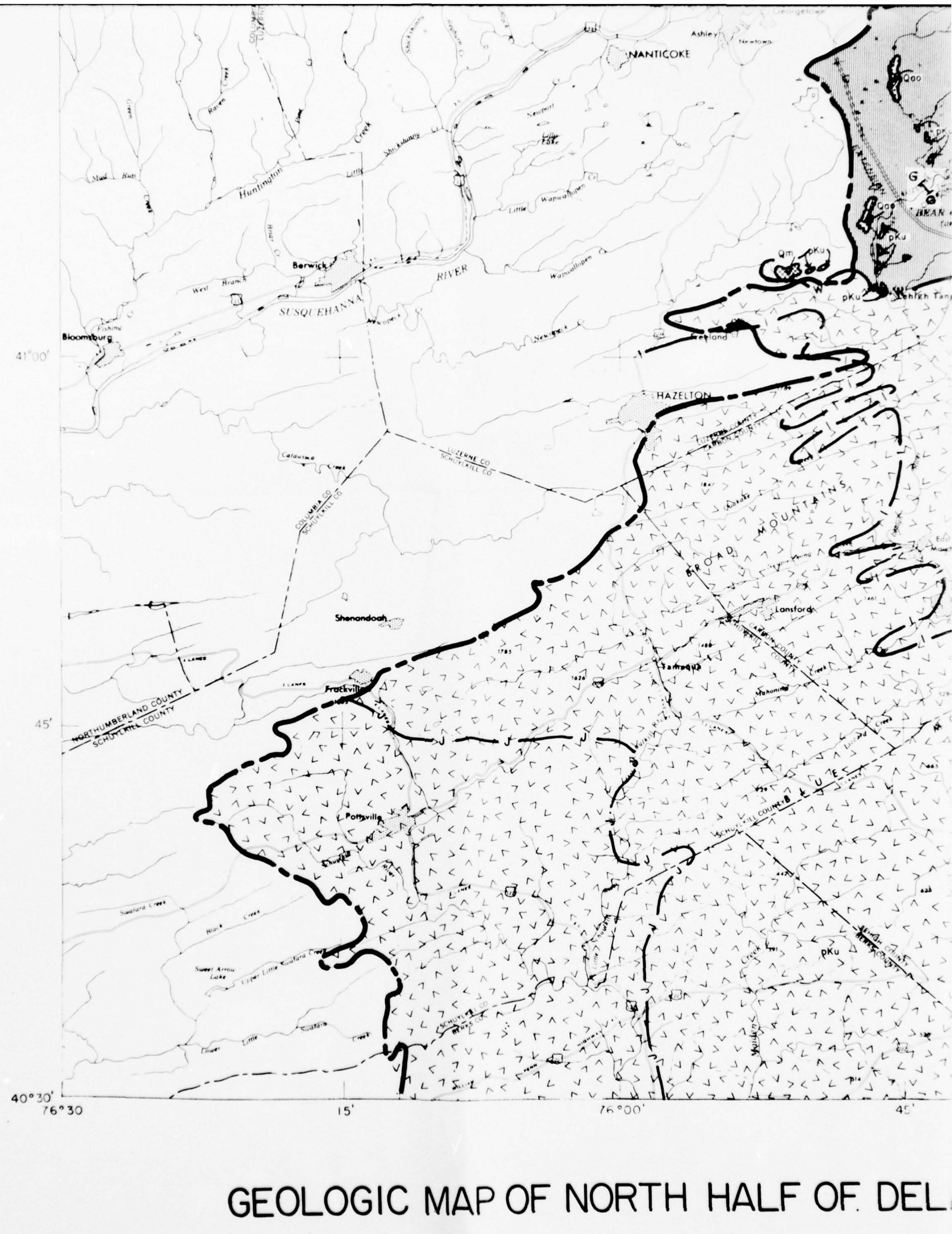
41°00′

PRE-CRETACEOUS
LACKAWANNA
PROMPTON F.C. RESERVOIR
(under construction)
Mayfield
Jermyn
Peckville
Winton
Dickson City
Olyphant
Throop
Dunmore
SCRANTON
BEAR CREEK RESERVOIR
(under construction)
Lehigh Tannery
MOUNTAINS
PENN FOREST RESERVOIR
(under construction)
WILD CREEK RESERVOIR
Lehighton
Palmerton
MONROE COUNTY
NORTHAMPTON COUNTY
DELAWARE
PENNSYLVANIA
NEW
Qao
Qt
Qms
pKu


NEWBURGH
Middletown
Goshen
Walden
Greenwood Lake
Sterling Lake
Wickham Lake
Round
Walton Lake
Tomahawk Lake
Beaver Dam Lake
Purgatory Swamp
Cranberry Pond
Spring Valley
Shungum Lake
NEW YORK
JERSEY
PENNSYLVANIA
NEW JERSEY
RIVER
Compiled from the following sources
(1) Soren, J.D., 1957, Unpublished mappin
the Delaware River basin
(2) Blanchard, N.H., and Lockwood, W.N
in Wayne, Pike, Monroe, Lackawann
(3) Merrill, F.J.H., Darton, N.H., Hollick
1902, U.S. Geol. Survey Geol. Atla
(4) Darton, N.H., Bayley, W.S., Salisbur
1908, U.S. Geol. Survey Geol. Atlas
(5) Spencer, A.C., Kummel, H.B., Wolff,
U.S. Geol. Survey Geol. Atlas, Fran
(6) Bayley, W.S., Salisbury, R.D., and K
U.S. Geol. Survey Geol. Atlas, Rar
(7) Lewis, J.V., and Kummel, H.B., 1910
and M.E. Johnson, 1950, Geologi
Dept. Conserv. and Econ. Devel. At
(8) Miller, B.L., and others, 1939, Nort
geology and geography: Pa. Geol. S
(9) Miller, B.L., and others, 1941, Lehi
geology and geography: Pa. Geol. S
(10) Lohman, S.W., 1937, Ground water i
Pa. Geol. Survey, 4th ser., Bull. W


NEWBURGH
Beacon
Walden
Middletown
Goshen
Goshen Reservoir
Purgatory Swamp
Tomahawk Lake
Beaver Dam Lake
Browns Pond Reservoir
Lake Washington
DUTCHESS
PUTNAM
Round
Walton Lake
Wickham Lake
Greenwood Lake
Sterling Lake
NEW YORK
JERSEY
Cranberry Pond
Spring Valley
Suffern
ROCKLAND
Pearl River
Ossining
Nyack
Tarrytown
Dobbs Ferry
30′
15′
41°00′
Compiled from the following sources
(1) Soren, J. D., 1957, Unpublished mapping in New York portion of the Delaware River basin
(2) Blanchard, N. H., and Lockwood, W. N., 1957, Unpublished mapping in Wayne, Pike, Monroe, Lackawanna, Luzerne, and Carbon Counties, Pa
(3) Merrill, F. J. H., Darton, N. H., Hollick, Arthur, and others, 1902, U. S. Geol. Survey Geol. Atlas, New York City folio (no. 83)
(4) Darton, N. H., Bayley, W. S., Salisbury, R. D., and Kummel, H. B., 1908, U. S. Geol. Survey Geol. Atlas, Passaic folio (no. 157)
(5) Spencer, A. C., Kummel, H. B., Wolff, J. E., and others, 1908, U. S. Geol. Survey Geol. Atlas, Franklin Furnace folio (no. 161)
(6) Bayley, W. S., Salisbury, R. D., and Kummel, H. B., 1914, U. S. Geol. Survey Geol. Atlas, Raritan folio (no. 191)
(7) Lewis, J. V., and Kummel, H. B., 1910-1912, revised by Kümmel, 1931, and M. E. Johnson, 1950, Geologic map of New Jersey: N. J. Dept. Conserv. and Econ. Devel. Atlas, sheet 40
(8) Miller, B. L., and others, 1939, Northampton County, Pennsylvania geology and geography: Pa. Geol. Survey, 4th ser., Bull. C 48, 495 p.
(9) Miller, B. L., and others, 1941, Lehigh County, Pennsylvania geology and geography: Pa. Geol. Survey, 4th ser., Bull. C 39, 492 p.
(10) Lohman, S. W., 1937, Ground water in northeastern Pennsylvania: Pa. Geol. Survey, 4th ser., Bull. W 4, 300 p.

8



GEOLOGIC MAP OF NORTH HALF OF DEL

E DELAWARE RIVER BASIN AND NORTHERN NEW JERSEY SH

SEY SHOWING UNCONSOLIDATED SEDIMENTS OF QUATERNAR

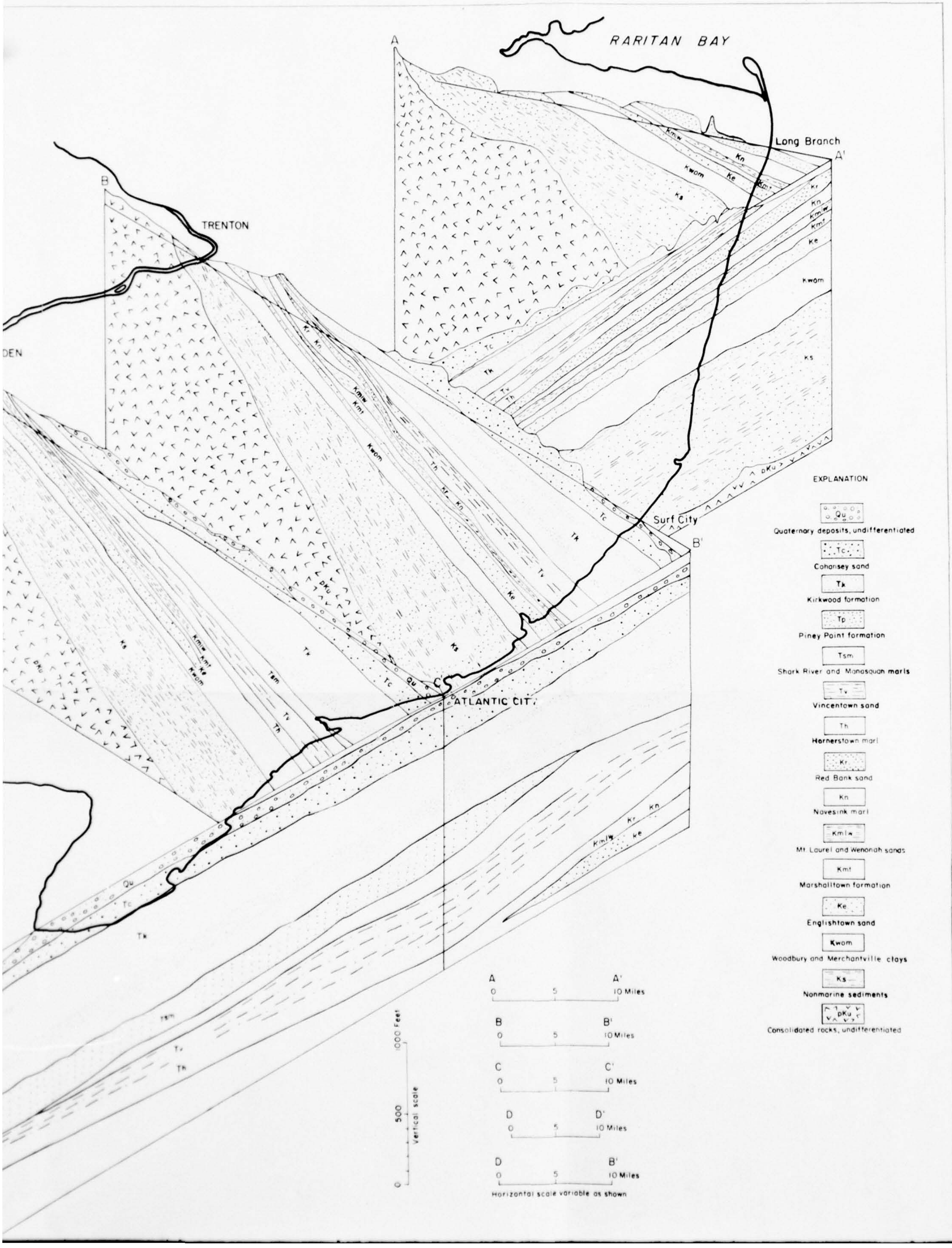
geology and geography: Pa. Geol. Survey, 4th ser., Bull. C 48, 495 p.
(9) Miller, B. L., and others, 1941, Lehigh County, Pennsylvania geology and geography: Pa. Geol. Survey, 4th ser., Bull. C 39, 492 p.
(10) Lohman, S. W., 1937, Ground water in northeastern Pennsylvania: Pa. Geol. Survey, 4th ser., Bull. W 4, 300 p.

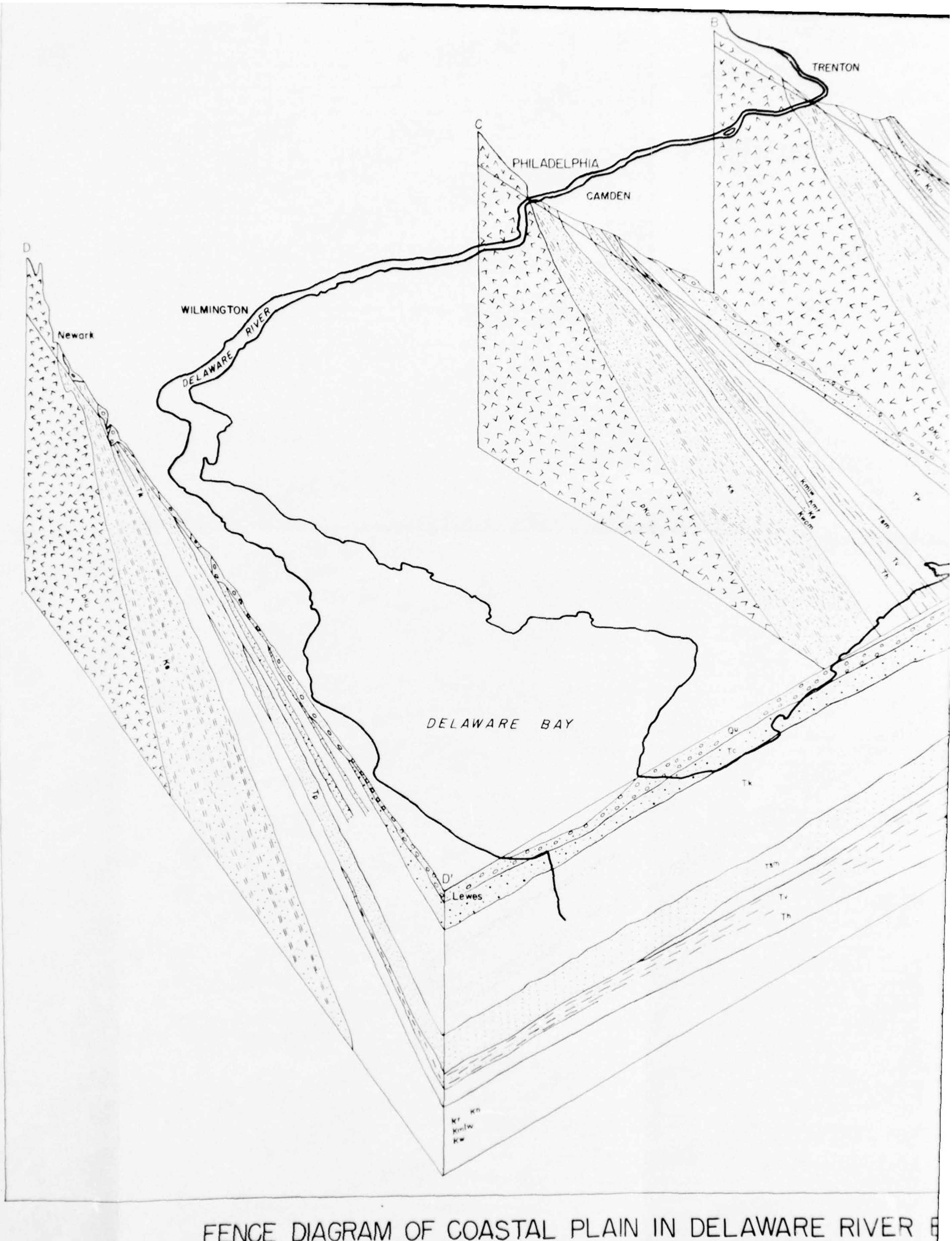
LIDATED SEDIMENTS OF QUATERNARY AGE

U.S. GEOLOGICAL SURVEY

2

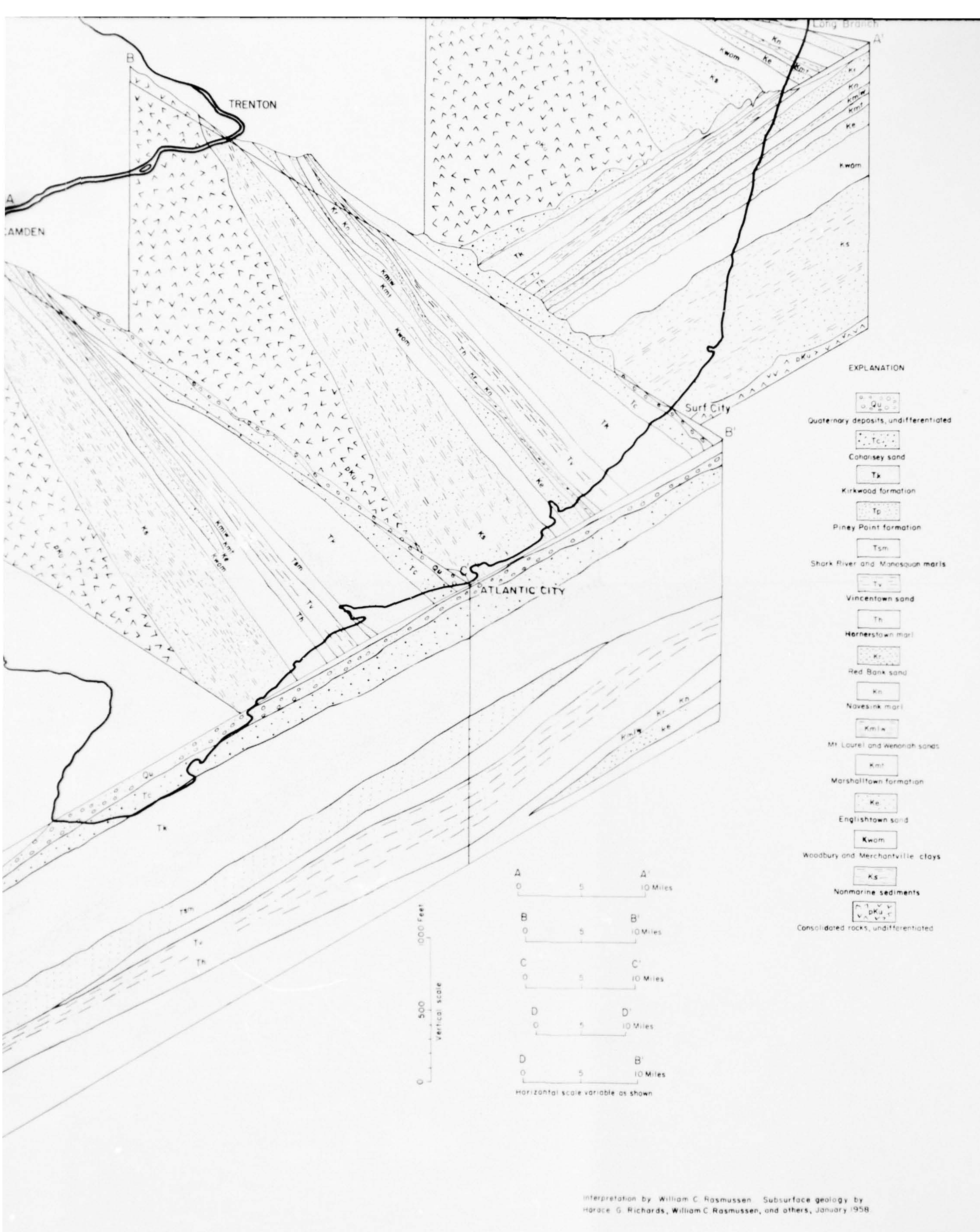
PLATE 5


RARITAN BAY
A
A'
B
B'
C'
TRENTON
DEN
Long Branch
Surf City
ATLANTIC CITY
EXPLANATION
Qu
Quaternary deposits, undifferentiated
Tc
Cohansey sand
Tk
Kirkwood formation
Tp
Piney Point formation
Tsm
Shark River and Manasquan marls
Tv
Vincentown sand
Th
Hornerstown marl
Kr
Red Bank sand
Kn
Navesink marl
Kmlw
Mt. Laurel and Wenonah sands
Kmt
Marshalltown formation
Ke
Englishtown sand
Kwom
Woodbury and Merchantville clays
Ks
Nonmarine sediments
pKu
Consolidated rocks, undifferentiated
A 0 5 A' 10 Miles
B 0 5 B' 10 Miles
C 0 5 C' 10 Miles
D 0 5 D' 10 Miles
D 0 5 B' 10 Miles
Horizontal scale variable as shown
Vertical scale
0 500 1000 Feet



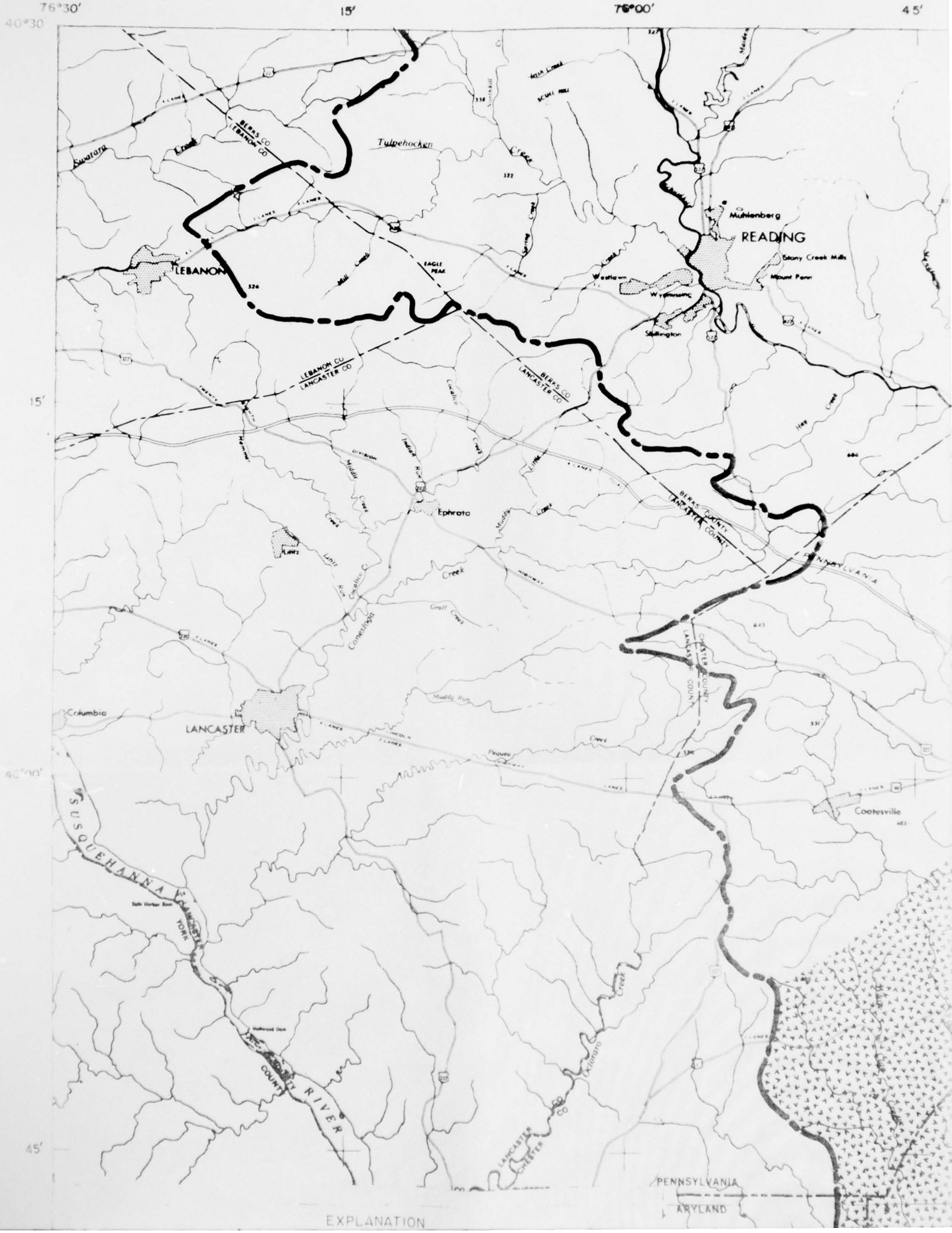
FENCE DIAGRAM OF COASTAL PLAIN IN DELAWARE RIVER B

ɱ



LAIN IN DELAWARE RIVER BASIN AND ADJACENT NEW JERSEY

U.S. GEOLOGICAL SURVEY



EXPLANATION

2


45'
30'
15'
75°00'
LEHIGH COUNTY
BUCKS COUNTY
HUNTERDON COUNTY
RIVER
Quakertown
Perkiomen
Creek
Souderton
PENNSYLVANIA
TURNPIKE
Doylestown
Lansdale
Pottstown
Royersford
Spring City
Phoenixville
NORRISTOWN
TURNPIKE
Coatesville
pKu
Tbm
Ks
Kwom
PHILADELPHIA
CAMDEN
Moorestown
Collingswood
CHESTER
WILMINGTON

1

3

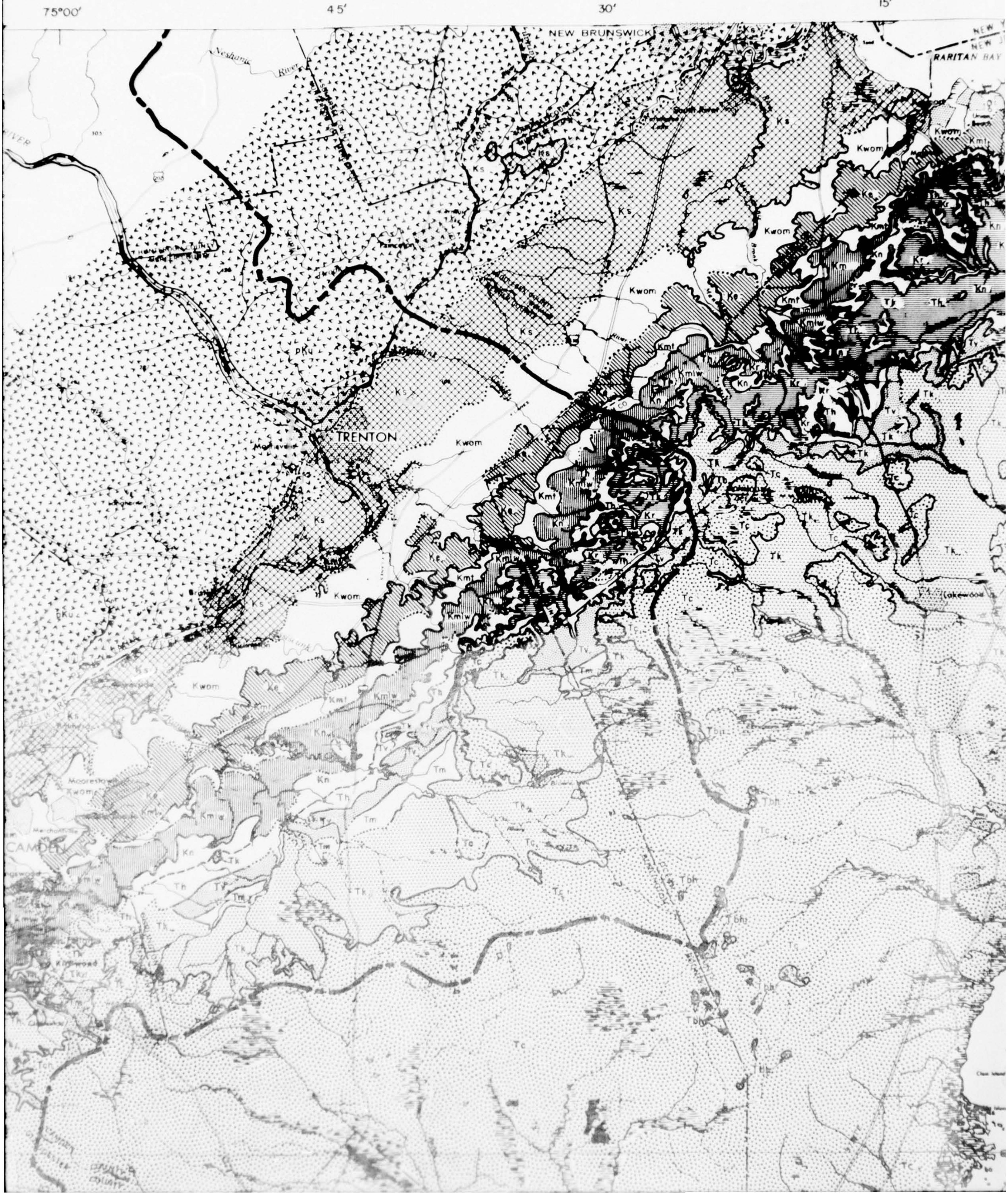

75°00'
45'
30'
15'
NEW BRUNSWICK
RARITAN BAY
TRENTON
CAMDEN
Moorestown
Lakewood
Neshaminy River
DELAWARE
RIVER
pKu
Ks
Kwom
Ke
Kmt
Kmlw
Kn
Kr
Th
Tk
Tv
Tm
Tc
Tbh

PLATE 6

30'
15'
74°00'
73°50'
40°30'
15'
40°00'
45'
NEW BRUNSWICK
NEW YORK
NEW JERSEY
RARITAN BAY
SANDY HOOK
Long Branch
Lakewood
BAY
BARNEGAT
Kwom
Ks
Ke
Kmt
Kmw
Kn
Kr
Th
Tbh
Tk
Tv
Tm
Tc

45'

EXPLANATION

Deposits of Quaternary age are omitted from this map; are shown on plate 7

TERTIARY

Pliocene(?)

Tbm

Bryn Mawr gravel

A remnant cap on Piedmont

Tbh

Beacon Hill gravel

A remnant cap on Coastal Plain

Miocene(?)

Tc

Cohansey sand

A highly permeable, extensive aquifer

Miocene

30'

Tk

Kirkwood formation

A formation containing several aquifers and aquicludes

Eocene

Tm

Manasquan marl

Includes overlying Shark River marl north of Asbury Park, N.J.

A minor but extensive aquiclude

Paleocene

Rancocas group

Tv

Vincentown sand

A minor aquifer

Th

Hornerstown marl

Together with the Navesink marl forms an extensive aquiclude

15'

CRETACEOUS

Upper Cretaceous

Monmouth group

Kr

Red Bank sand

Includes Tinton sand member in Monmouth County, N.J.

A minor aquifer in New Jersey outside the basin

Kn

Navesink marl

Together with the Hornerstown marl forms an extensive aquiclude

Kmlw

Mount Laurel and Wenonah sands

An extensive minor aquifer

39°00'

Kmt

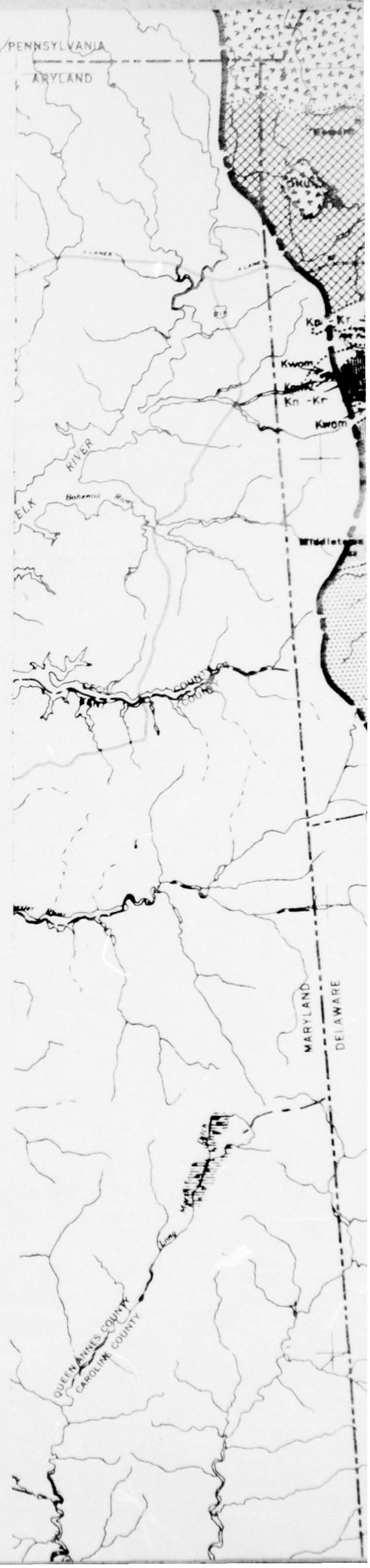
Marshalltown formation

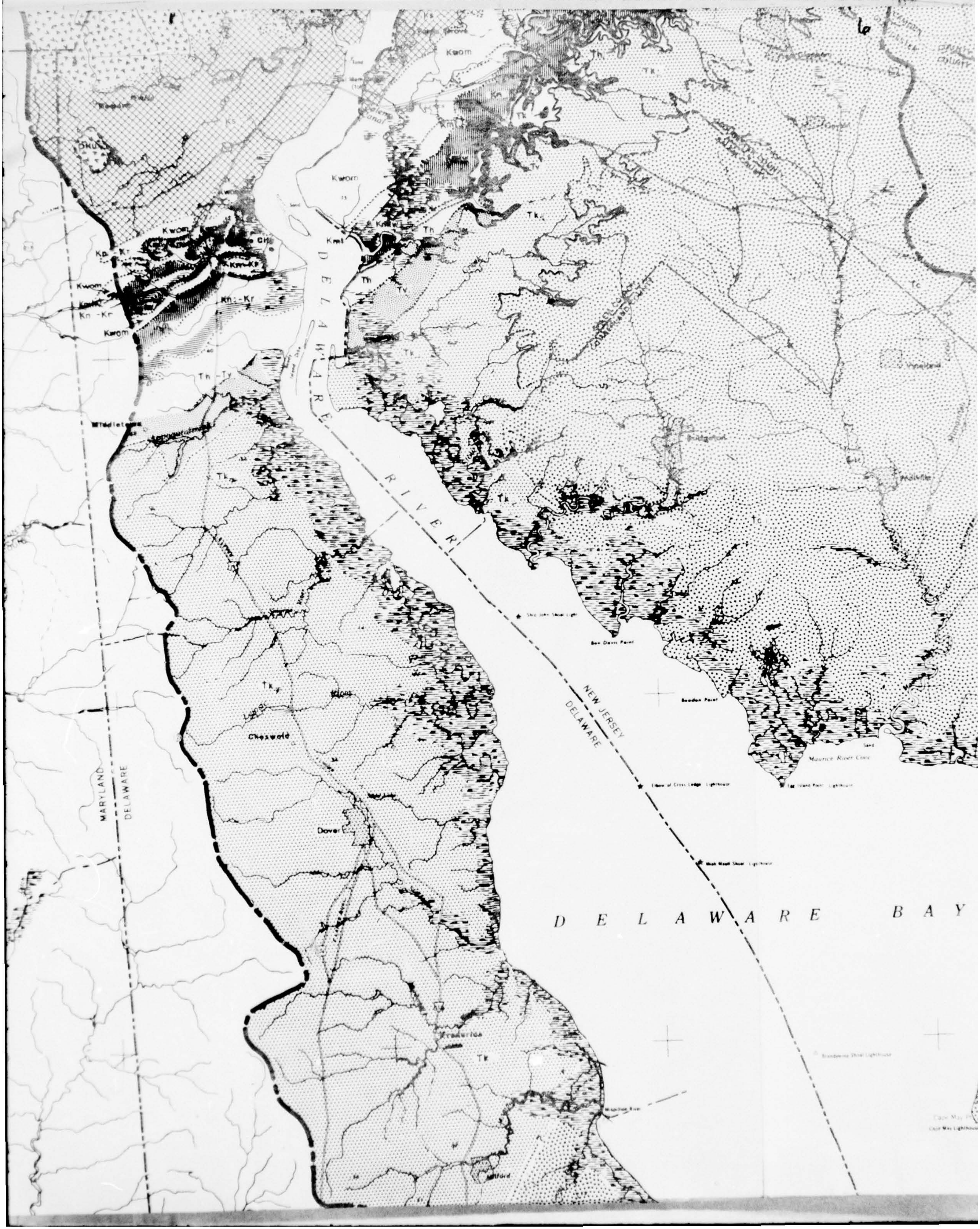
An extensive thin aquiclude. Contiguous with the Woodbury and Merchantville clays southwest of Swedesboro, N.J.

Matawan group

Ke

Englishtown sand




DELAWARE RIVER
DELAWARE BAY
NEW JERSEY
DELAWARE
MARYLAND
DELAWARE
Kwom
Kn-Kr
Th-Ty
Tk
Tc
Cheswold
Dover
Ship John Shoal Light
Ben Davis Point
Maurice River Cove
Elbow of Cross Ledge Lighthouse
Brandywine Shoal Lighthouse
Mispillion River


1
Brant Beach
LITTLE EGG HARBOR
GREAT BAY
Seven Islands
Reed Bay
Pleasantville
Brigantine City
Absecon Inlet
ATLANTIC CITY
Ventnor
Margate City
Great Egg Inlet
Ocean City
Carson Inlet
Ludlam Bay
Townsend Inlet
Great Sound
Hereford Inlet
North Wildwood
Wildwood
Cape May Inlet
Cape May Lighthouse
Cape May
BAY
ATLANTIC OCEA


7
8
Surf City
Beach Arlington
Brant Beach
Long
LITTLE EGG HARBOR
Spray Beach
Beach Haven
GREAT BAY
Seven Islands
Pleasantville
Brigantine City
Absecon Inlet
ATLANTIC CITY
Ventnor
Margate City
Ocean City
ATLANTIC OCEAN
30′
15′
39°00′

A minor aquifer in New Jersey outside the basin

Monmouth group

Kn

Navesink marl

Together with the Hornerstown marl forms an extensive aquiclude

Kmlw

Mount Laurel and Wenonah sands

An extensive minor aquifer

Upper Cretaceous

Kmt

Marshalltown formation

An extensive thin aquiclude. Contiguous with the Woodbury and Merchantville clays southwest of Swedesboro, N.J.

Matawan group

Ke

Englishtown sand

A minor aquifer. Wedges out southwest of Swedesboro, N.J.

Kwom

Woodbury and Merchantville clays

A major thick aquiclude

CRETACEOUS

Lower and Upper Cretaceous

Ks

Nonmarine formations

A system of important channel-fill aquifers and lenticular aquicludes. Includes Magothy and Raritan formations (Upper Cretaceous) in New Jersey; Magothy, Raritan and Patapsco formations (Upper Cretaceous) and Patuxent formation (Lower Cretaceous) in Delaware

PRE-CRETACEOUS

pKu

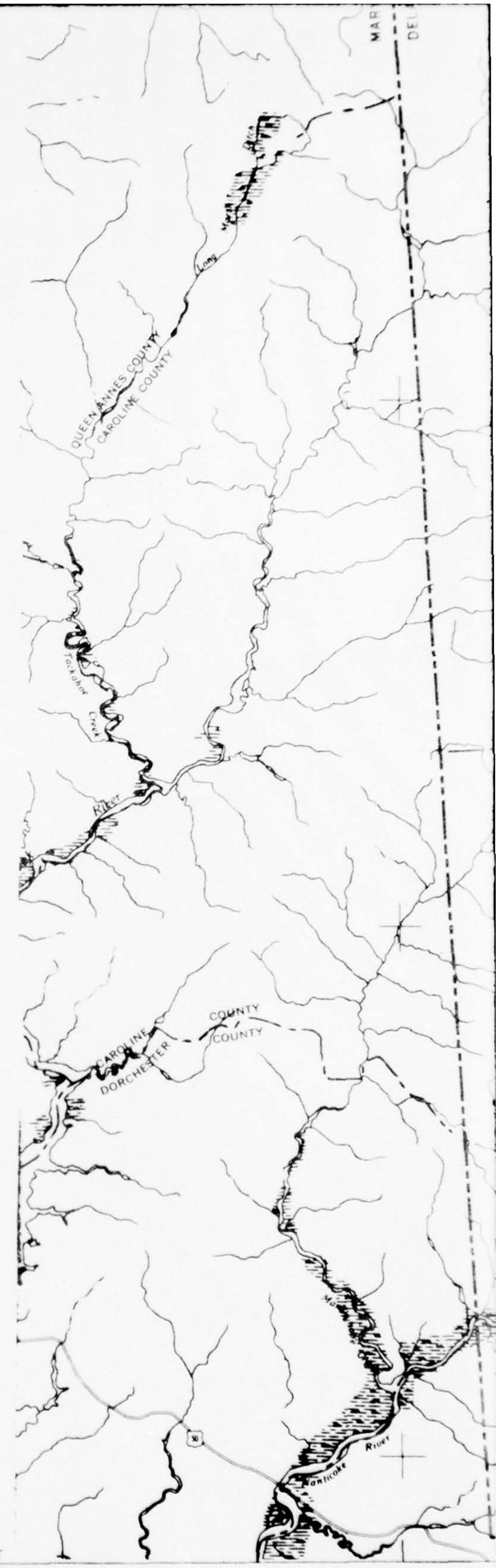
Consolidated rocks, undifferentiated

Subdivisions shown on pl. II

Geologic contact

Dashed where uncertain; dotted where concealed

Boundary of Delaware River basin



39°00'

45'

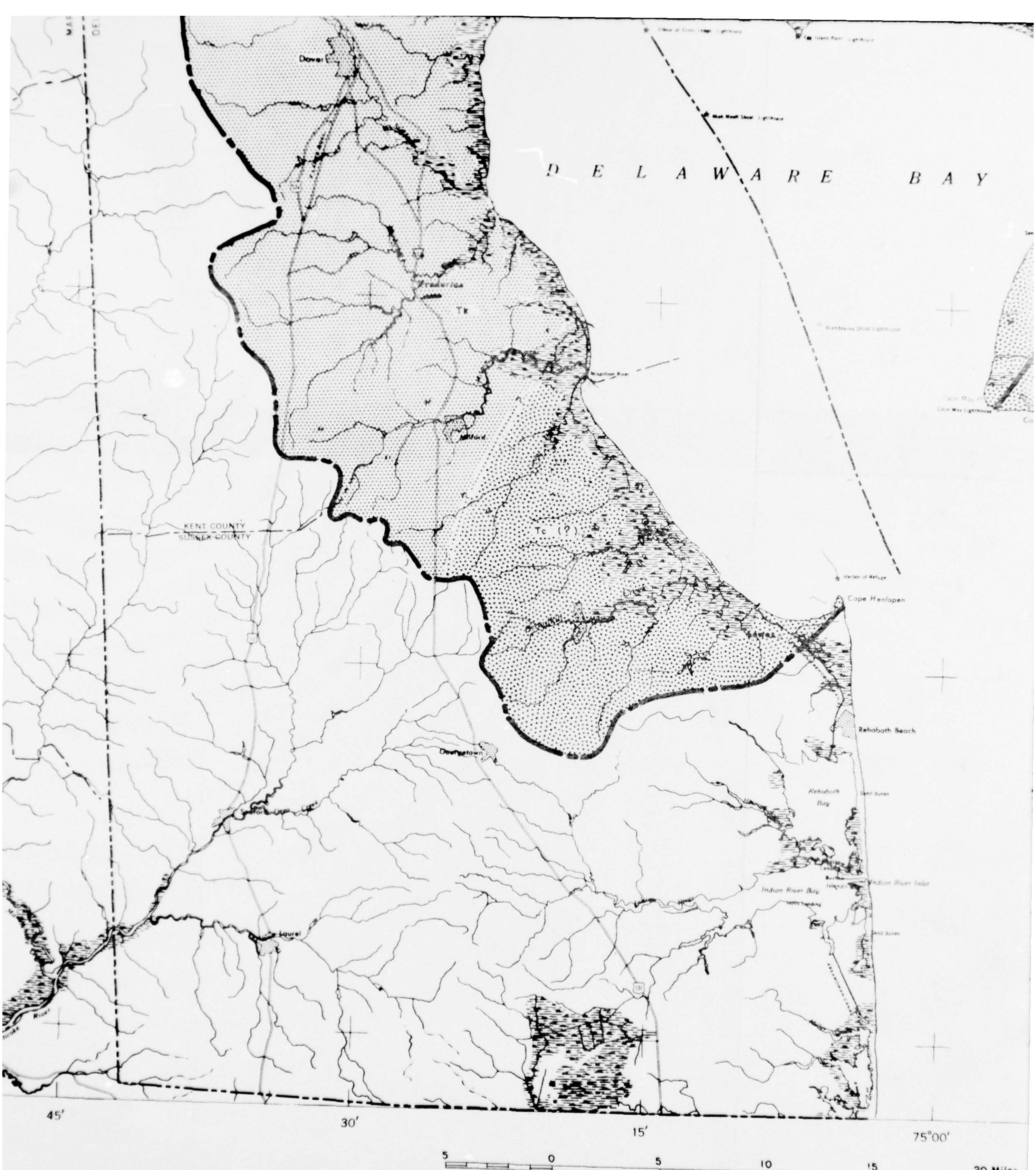
30'

38°27'

76°30' 15' 76°00' 45'

GEOLOGIC MAP OF SOUTH HALF OF DELAWARE RI

9



ARE RIVER BASIN AND SOUTHERN NEW JERSEY SHOWING

Compiled from the following sources

(1) Lewis, J. V., and Kümmel, H. B., ...
and M. E. Johnson, 1950, ...
Conserv. and Econ. Devel. ...

(2) Bascom, Florence, and Mill...
Atlas, Elkton-Wilmington ...

(3) Miller, B. L., 1906, U. S. Geo...

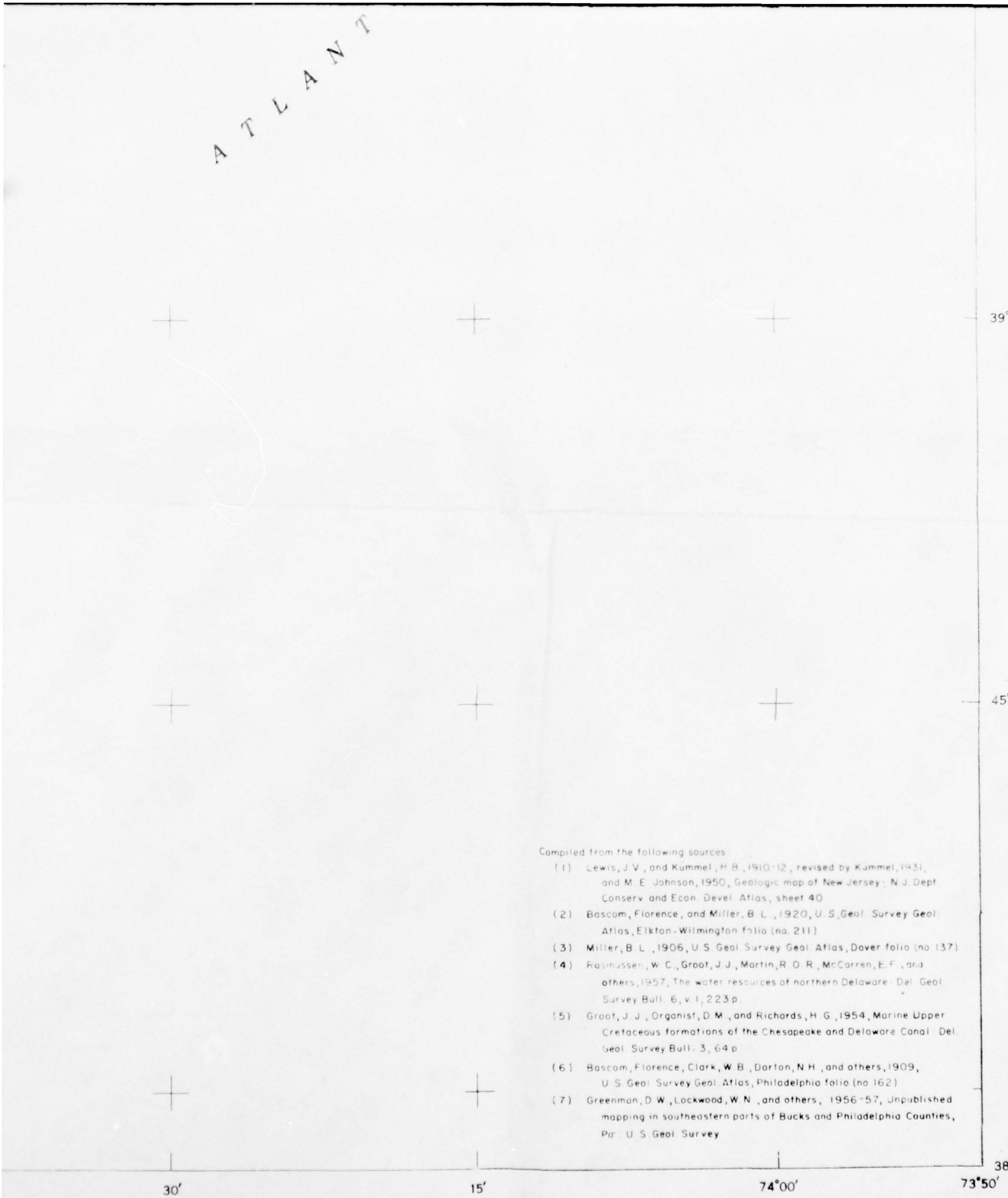
(4) Rasmussen, W. C., Groot, J. J. ...
others, 1957, The water re...
Survey Bull. 6, v. 1, 223 p...

(5) Groot, J. J., Organist, D. M., ...
Cretaceous formations o...
Geol. Survey Bull. 3, 64 p...

(6) Bascom, Florence, Clark, W. ...
U. S. Geol. Survey Geol. At...

(7) Greenman, D. W., Lockwood, W. ...
mapping in southeastern ...
Pa.: U. S. Geol. Survey

...G UNCONSOLIDATED SEDIMENTS OF CRETACEOUS AND TERT...



Compiled from the following sources

(1) Lewis, J V, and Kummel, H B, 1910-12, revised by Kummel, 1931, and M E Johnson, 1950, Geologic map of New Jersey: N J Dept Conserv and Econ Devel Atlas, sheet 40

(2) Bascom, Florence, and Miller, B L, 1920, U S Geol Survey Geol Atlas, Elkton-Wilmington folio (no. 211)

(3) Miller, B L, 1906, U S Geol Survey Geol Atlas, Dover folio (no 137)

(4) Rasmussen, W C, Groot, J J, Martin, R O R, McCarren, E F, and others, 1957, The water resources of northern Delaware: Del Geol Survey Bull 6, v 1, 223 p

(5) Groot, J J, Organist, D M, and Richards, H G, 1954, Marine Upper Cretaceous formations of the Chesapeake and Delaware Canal: Del Geol Survey Bull 3, 64 p

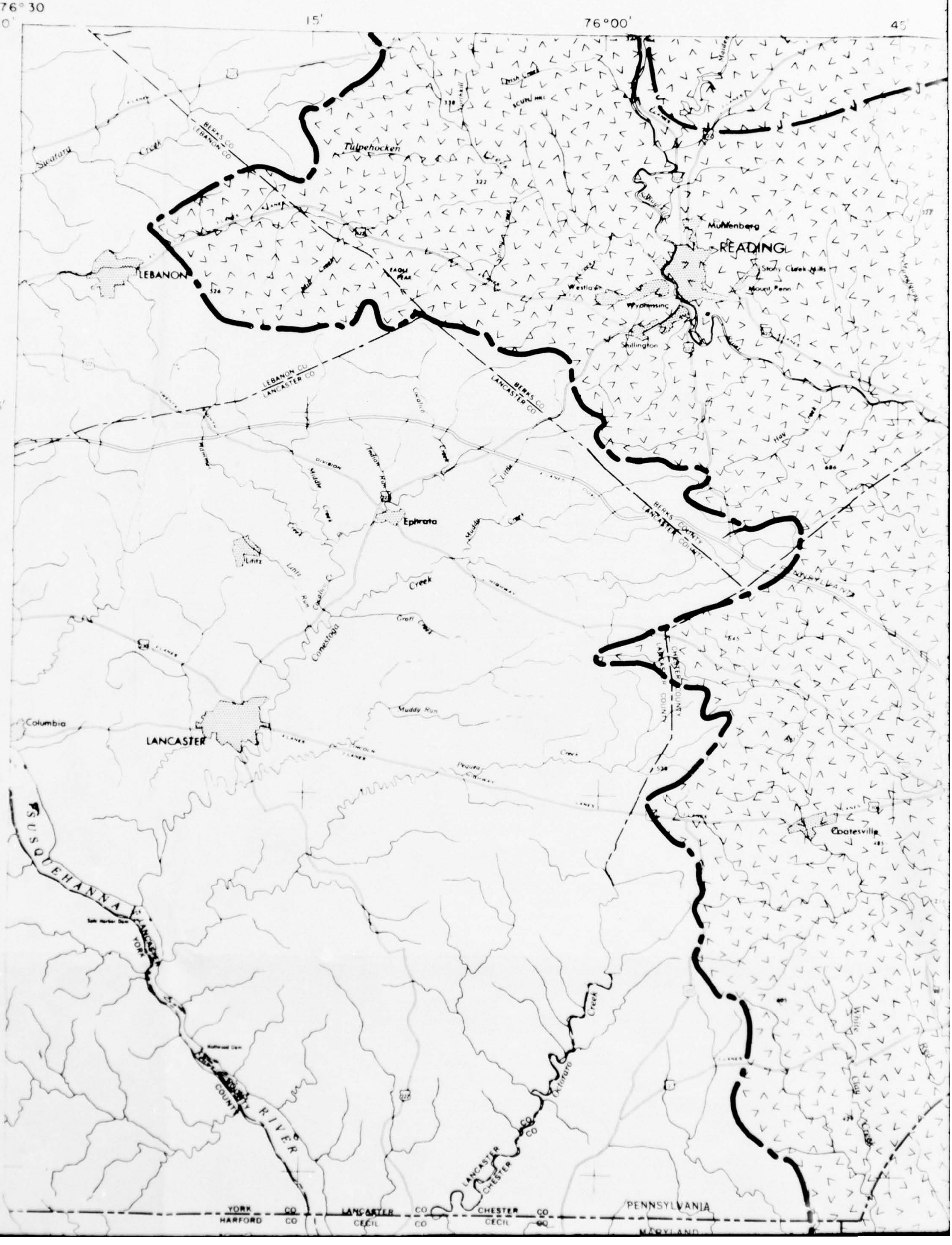
(6) Bascom, Florence, Clark, W B, Darton, N H, and others, 1909, U S Geol Survey Geol Atlas, Philadelphia folio (no 162)

(7) Greenman, D W, Lockwood, W N, and others, 1956-57, Unpublished mapping in southeastern parts of Bucks and Philadelphia Counties, Pa: U S Geol Survey

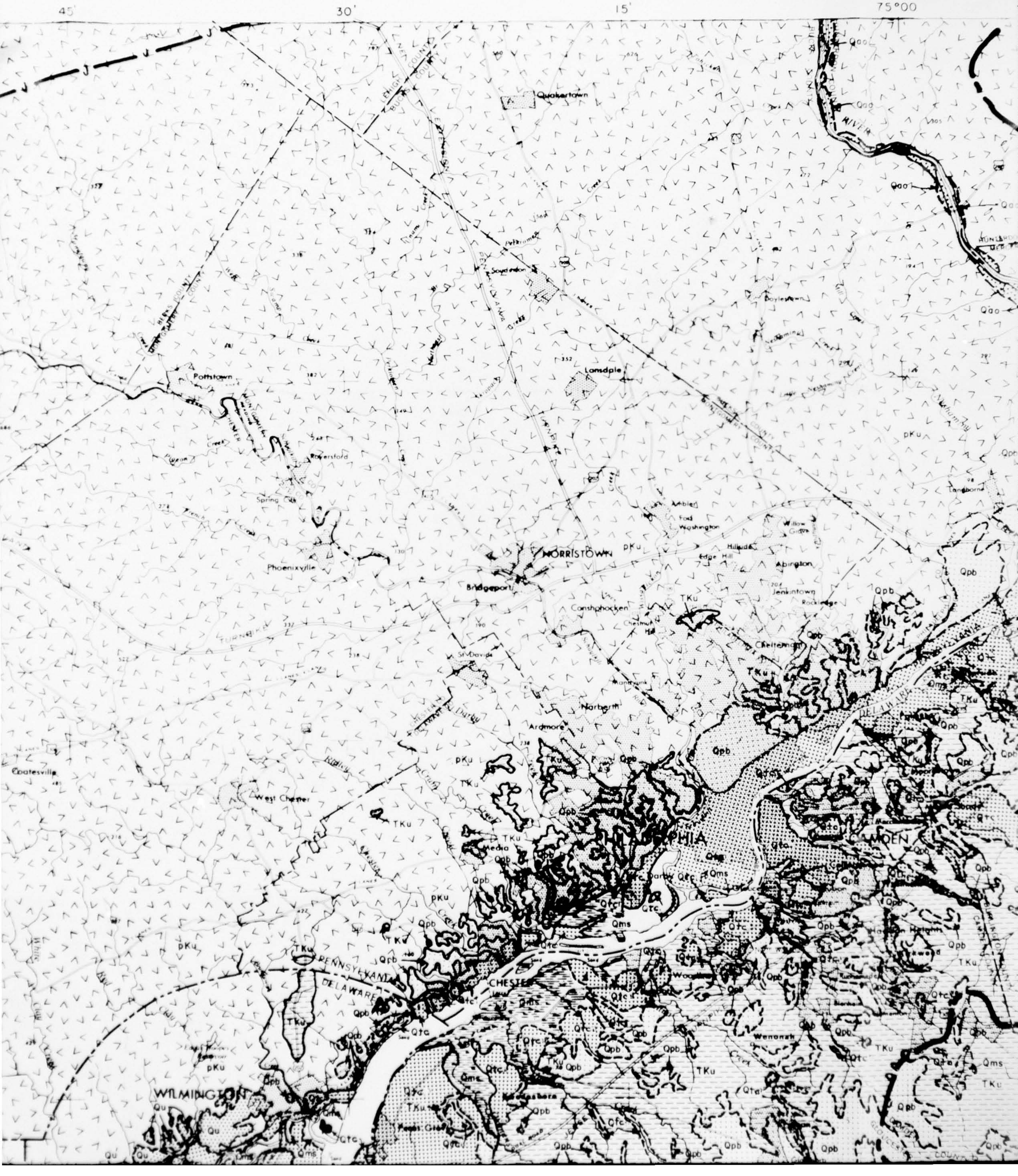
SEDIMENTS OF CRETACEOUS AND TERTIARY AGE

11 12

U.S. GEOLOGICAL SURVEY

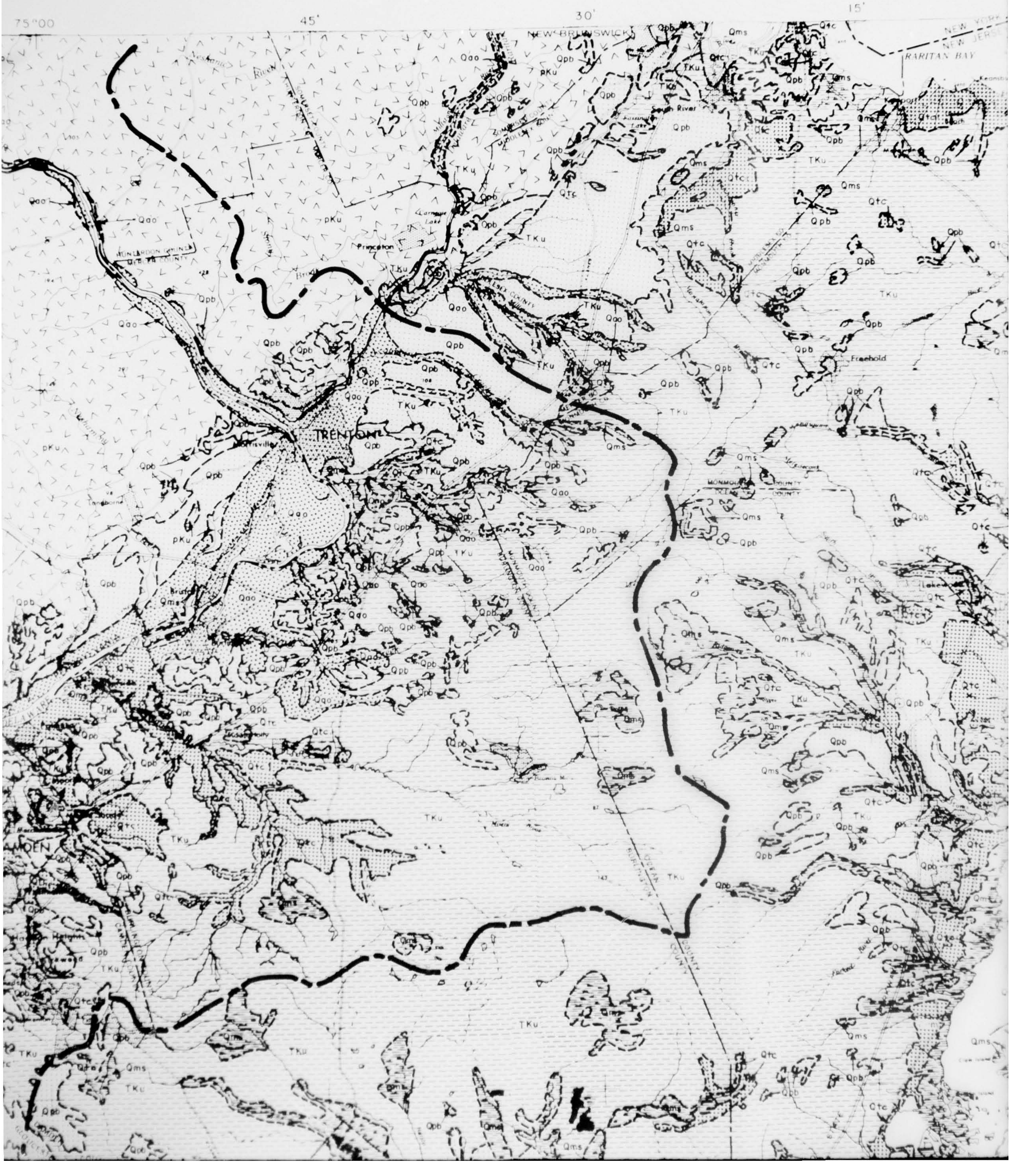


8



45'
30'
15'
75°00'
Quakertown
RIVER
Qao
Doylestown
Lansdale
Pottstown
Royersford
Spring City
Phoenixville
NORRISTOWN
Bridgeport
Ambler
Fort Washington
Willow Grove
Hillside
Edge Hill
Abington
Jenkintown
Rockledge
Conshohocken
Chestnut Hill
Cheltenham
Manayunk
Narberth
Ardmore
St. Davids
TURNPIKE
Coatesville
West Chester
Media
CHESTER
PENNSYLVANIA
DELAWARE
WILMINGTON
Wenonah
Woodbury
CAMDEN
Langhorne
pKu
TKu
Qpb
Qtc
Qms
Qu

1 3

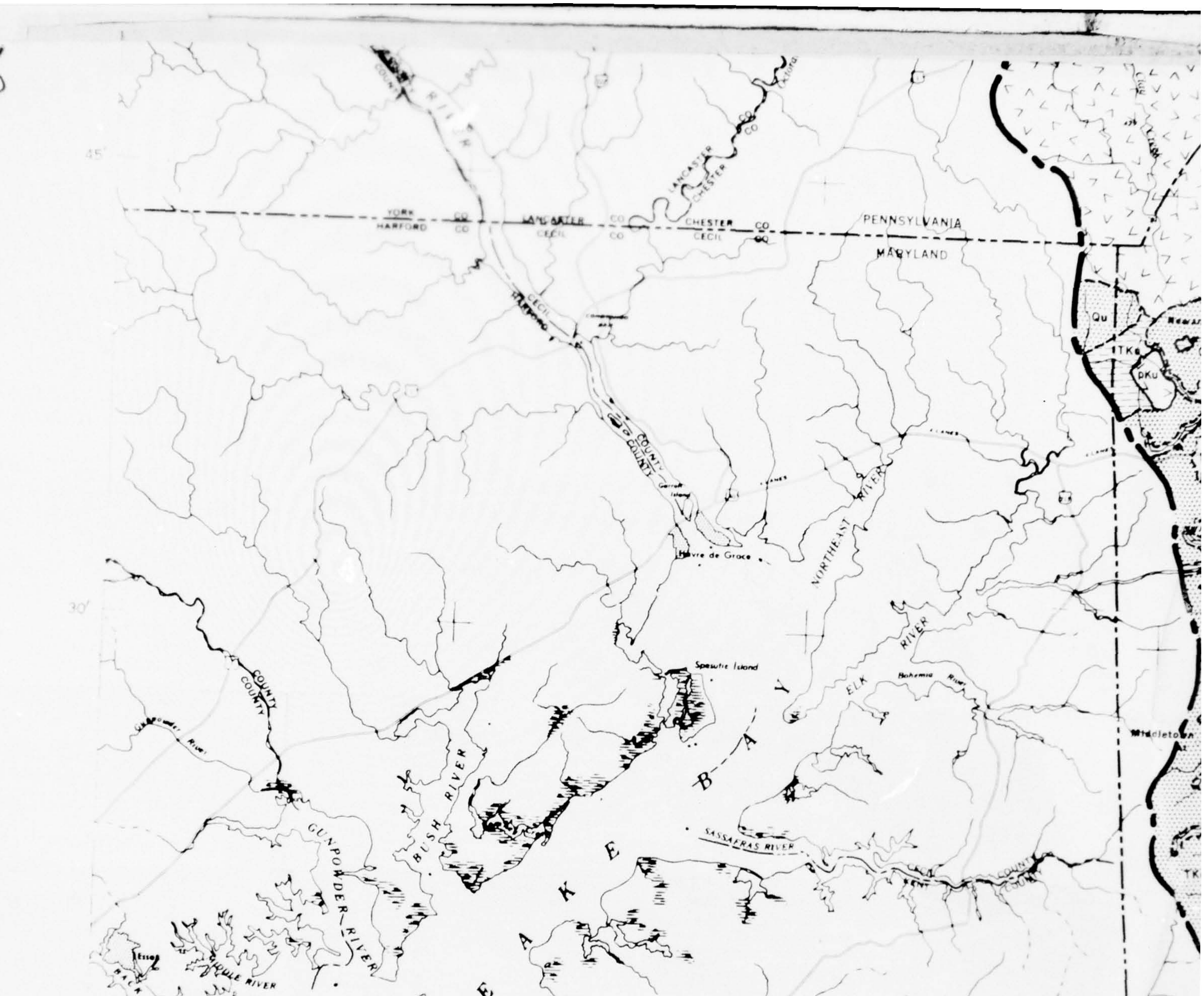

75°00'
45'
30'
15'
NEW BRUNSWICK
NEW YORK
NEW JERSEY
RARITAN BAY
South River
Princeton
TRENTON
Freehold
Qpb
Qao
Qms
Qtc
TKu
pKu

4

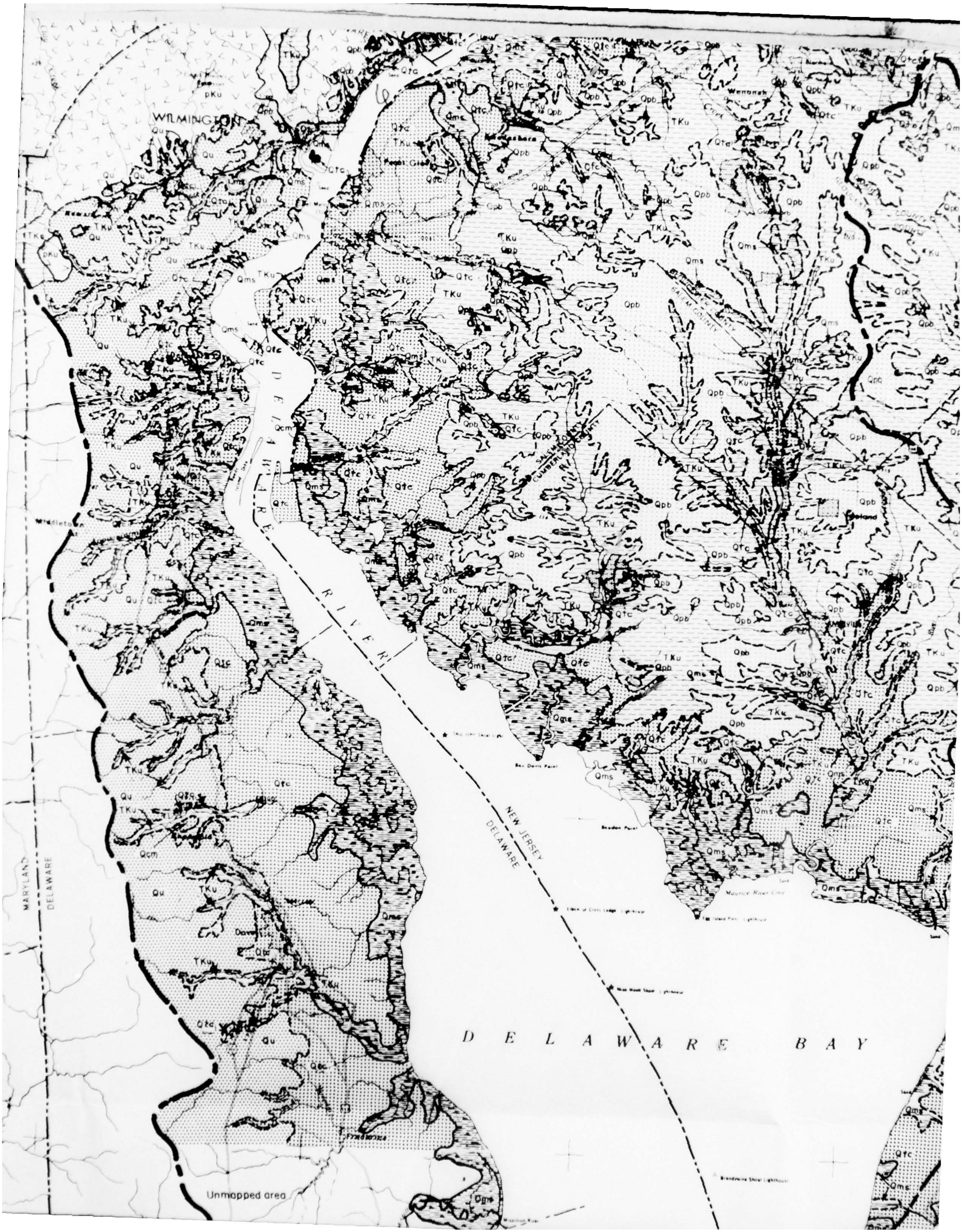
PLATE 7


30'
15'
74°00'
73°50'
40°30'
15
40°00'
45'
NEW BRUNSWICK
NEW YORK
NEW JERSEY
RARITAN BAY
Keansburg
East Keansburg
Atlantic Highlands
Belford
Freehold
Long Branch
BARNEGAT
BAY
MONMOUTH COUNTY
OCEAN COUNTY
BURLINGTON
Qpb
Qms
Qtc
TKu
Qao
Qbd
pKu

5



EXPLANATION

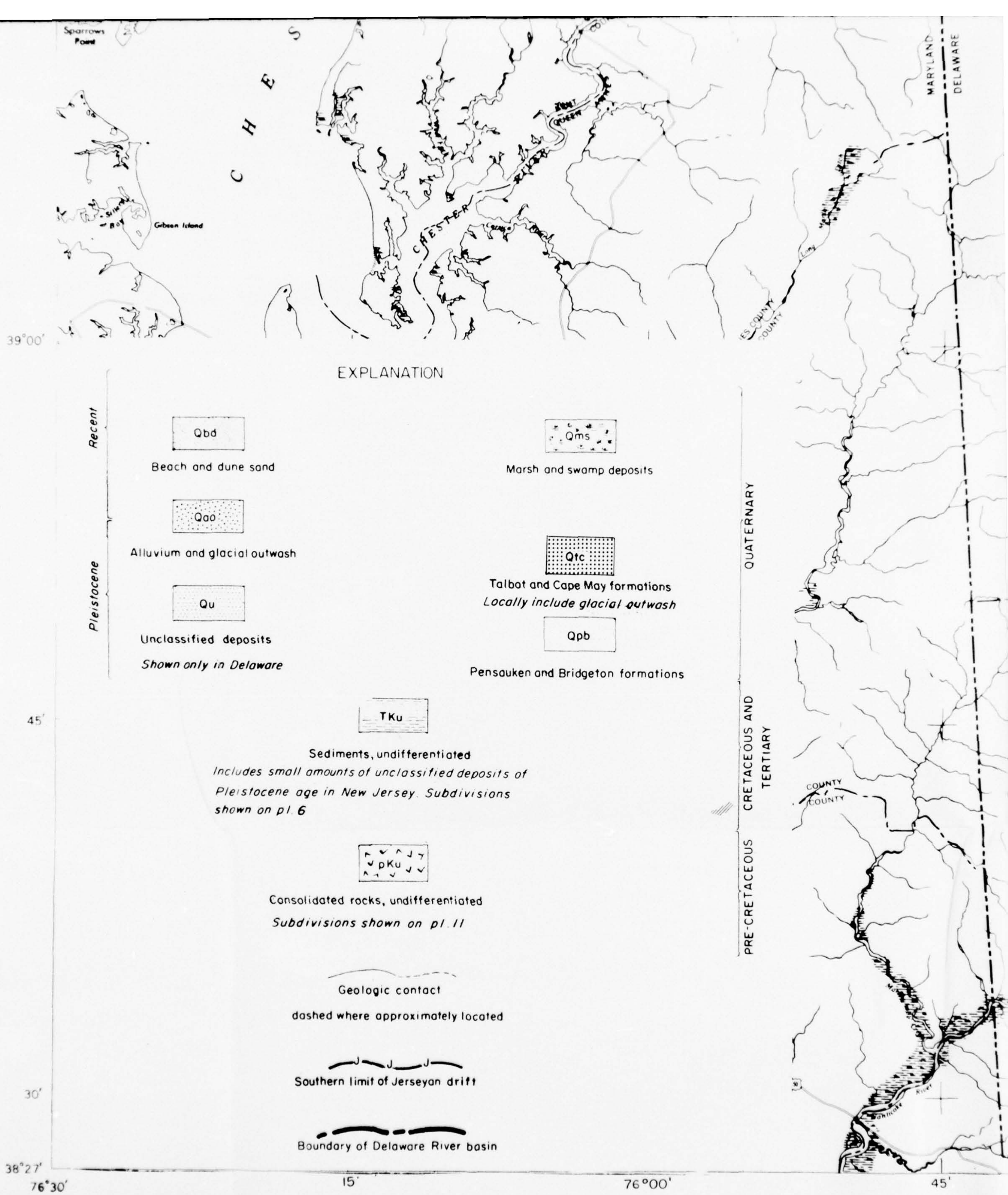


WILMINGTON
DELAWARE
RIVER
DELAWARE BAY
NEW JERSEY
DELAWARE
MARYLAND
SALEM COUNTY
CUMBERLAND COUNTY
Middletown
Ben Davis Point
Maurice River Cove
Unmapped area
Qpb
Qtc
Qms
TKu
Qu
pKu
Qcm


ATLANTIC OCEAN
ATLANTIC CITY
Ventnor
Margate City
Ocean City
Wildwood
North Wildwood
Hereford Inlet
Townsend Inlet
Corson Inlet
Great Egg Inlet
Absecon Inlet
GREAT BAY
LITTLE EGG HARBOR
Great Sound
Hammonton
Qbd
Qms
Qtc
Qpb
TKu
Y

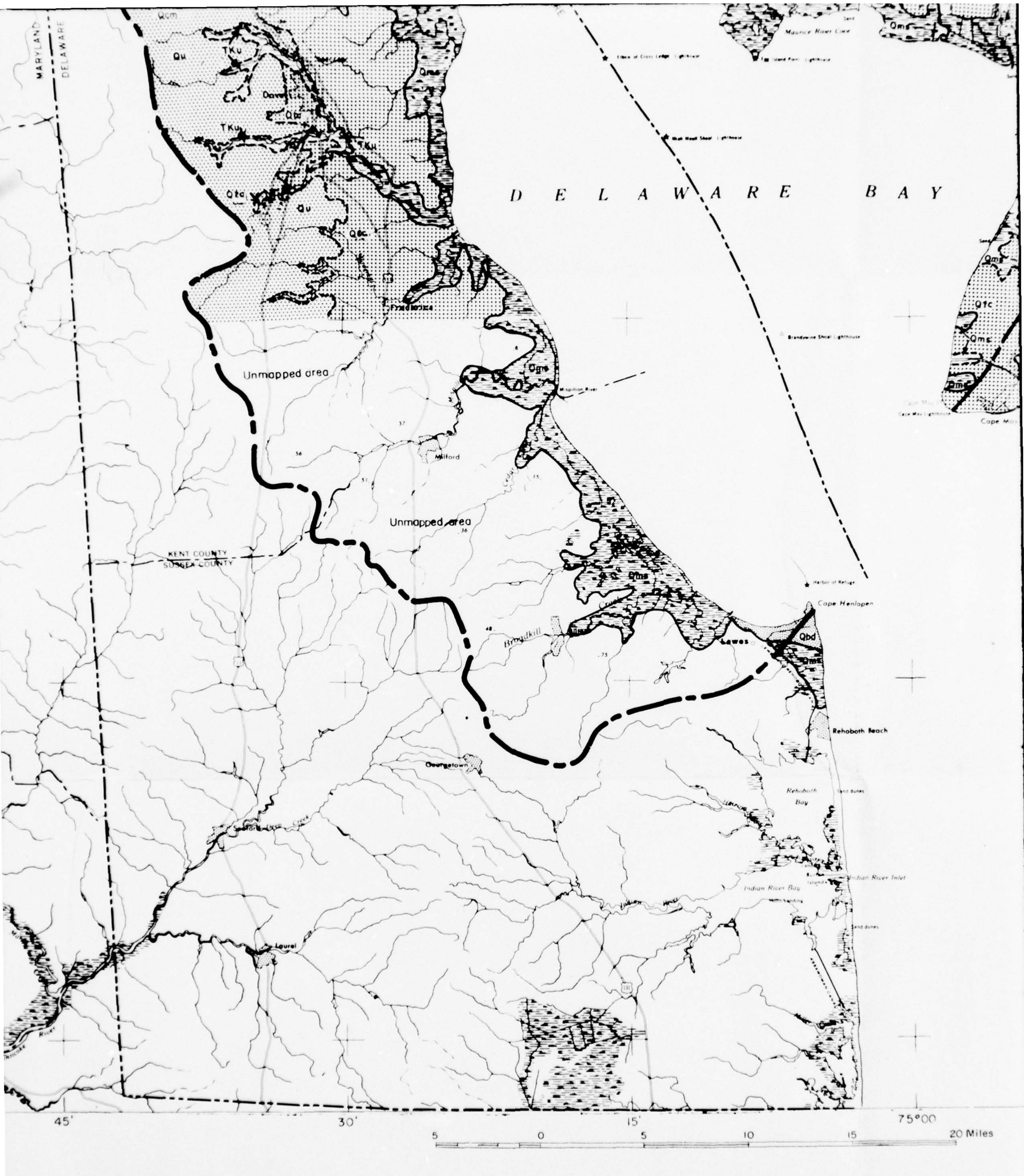
8

TKu
Qms
Qtc
Qpb
Qbd
45′
30′
15′
39°00′
LITTLE EGG HARBOR
GREAT BAY
Brant Beach
Long Beach
Clam Island
Seven Islands
Absecon Inlet
ATLANTIC CITY
Ventnor
Margate City
Great Egg Inlet
Ocean City
Corson Inlet
ATLANTIC OCEAN



GEOLOGIC MAP OF SOUTH HALF OF DELAW

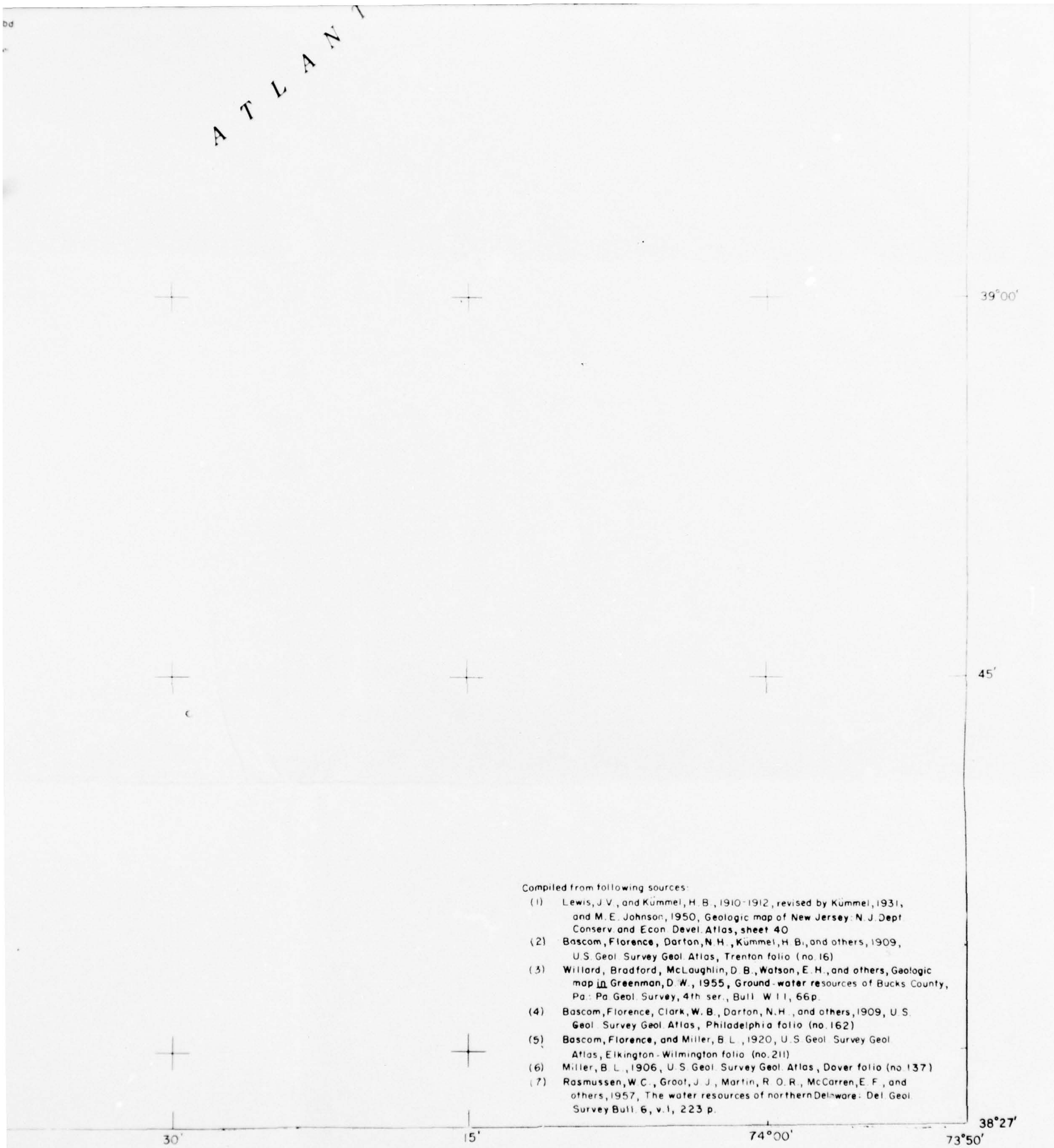
9



F DELAWARE RIVER BASIN AND SOUTHERN NEW JERSEY SH

10

V JERSEY SHOWING UNCONSOLIDATED SEDIMENTS OF QUAT



Compiled from following sources:

(1) Lewis, J. V., and Kümmel, H. B., 1910-1912, revised by Kümmel, 1931, and M. E. Johnson, 1950, Geologic map of New Jersey: N. J. Dept. Conserv. and Econ. Devel. Atlas, sheet 40

(2) Bascom, Florence, Darton, N. H., Kümmel, H. B., and others, 1909, U. S. Geol. Survey Geol. Atlas, Trenton folio (no. 16)

(3) Willard, Bradford, McLaughlin, D. B., Watson, E. H., and others, Geologic map <u>in</u> Greenman, D. W., 1955, Ground-water resources of Bucks County, Pa.: Pa. Geol. Survey, 4th ser., Bull. W 11, 66p.

(4) Bascom, Florence, Clark, W. B., Darton, N. H., and others, 1909, U. S. Geol. Survey Geol. Atlas, Philadelphia folio (no. 162)

(5) Bascom, Florence, and Miller, B. L., 1920, U. S. Geol. Survey Geol. Atlas, Elkington-Wilmington folio (no. 211)

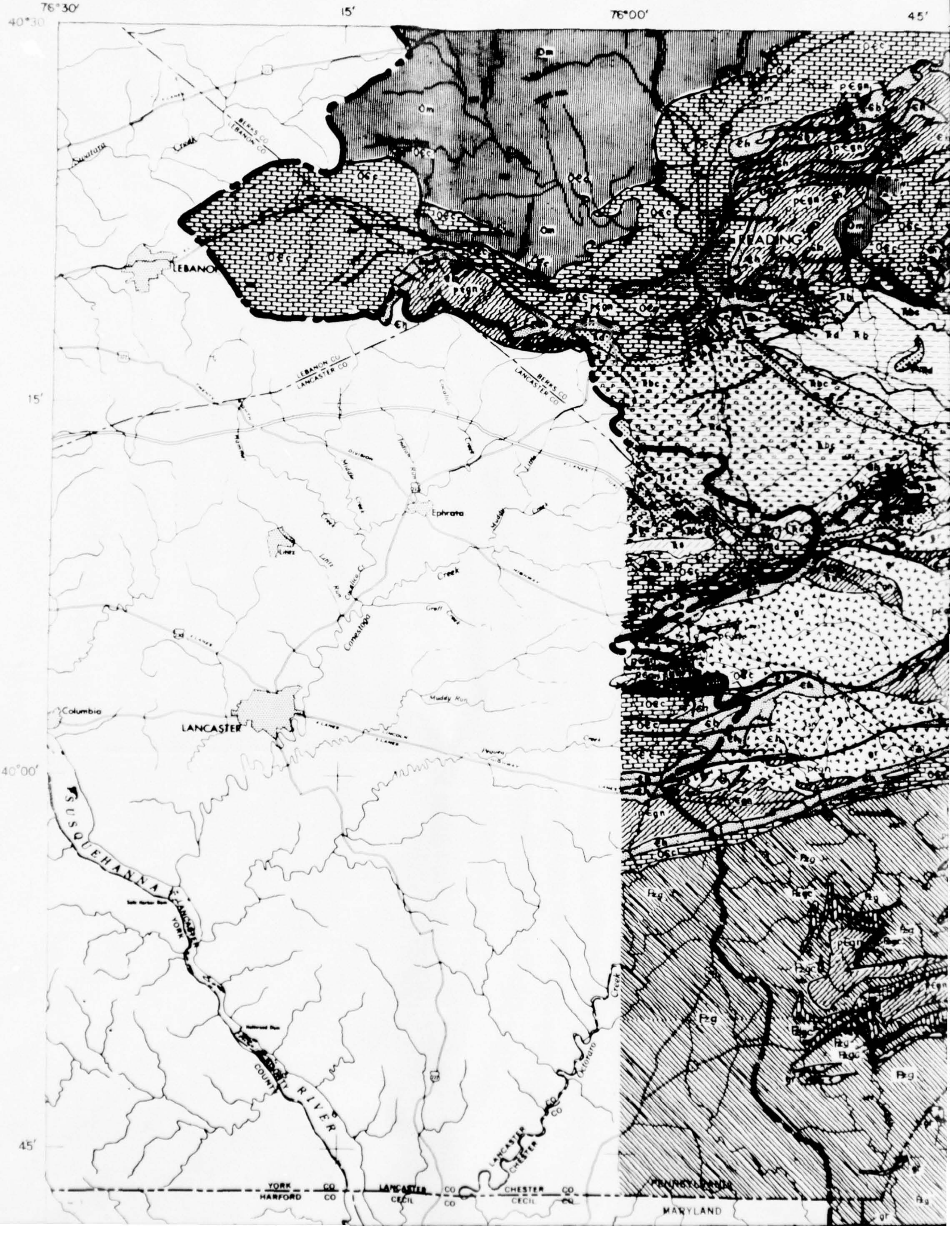
(6) Miller, B. L., 1906, U. S. Geol. Survey Geol. Atlas, Dover folio (no. 137)

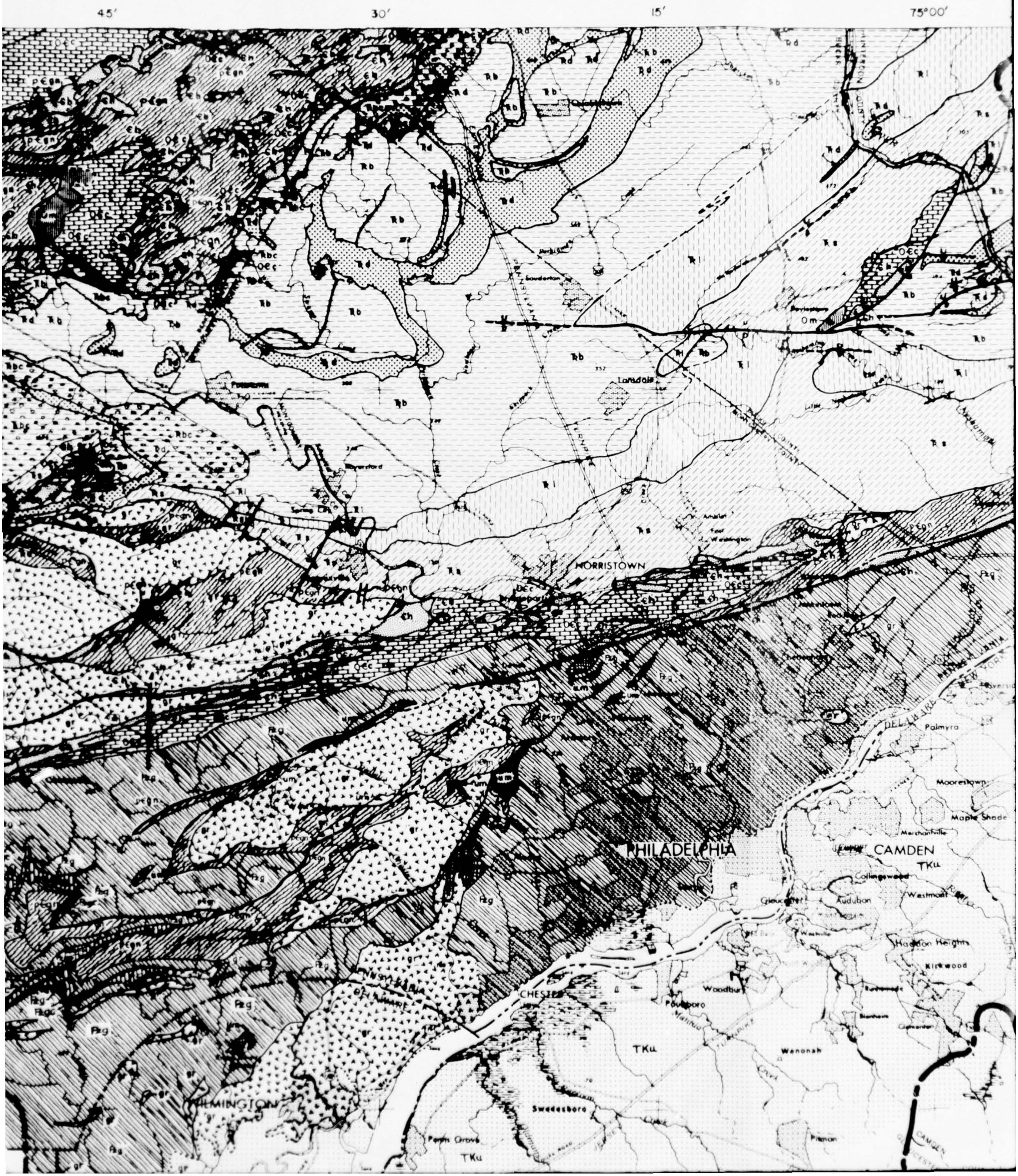
(7) Rasmussen, W. C., Groot, J. J., Martin, R. O. R., McCarren, E. F., and others, 1957, The water resources of northern Delaware: Del. Geol. Survey Bull. 6, v. 1, 223 p.

LIDATED SEDIMENTS OF QUATERNARY AGE

12

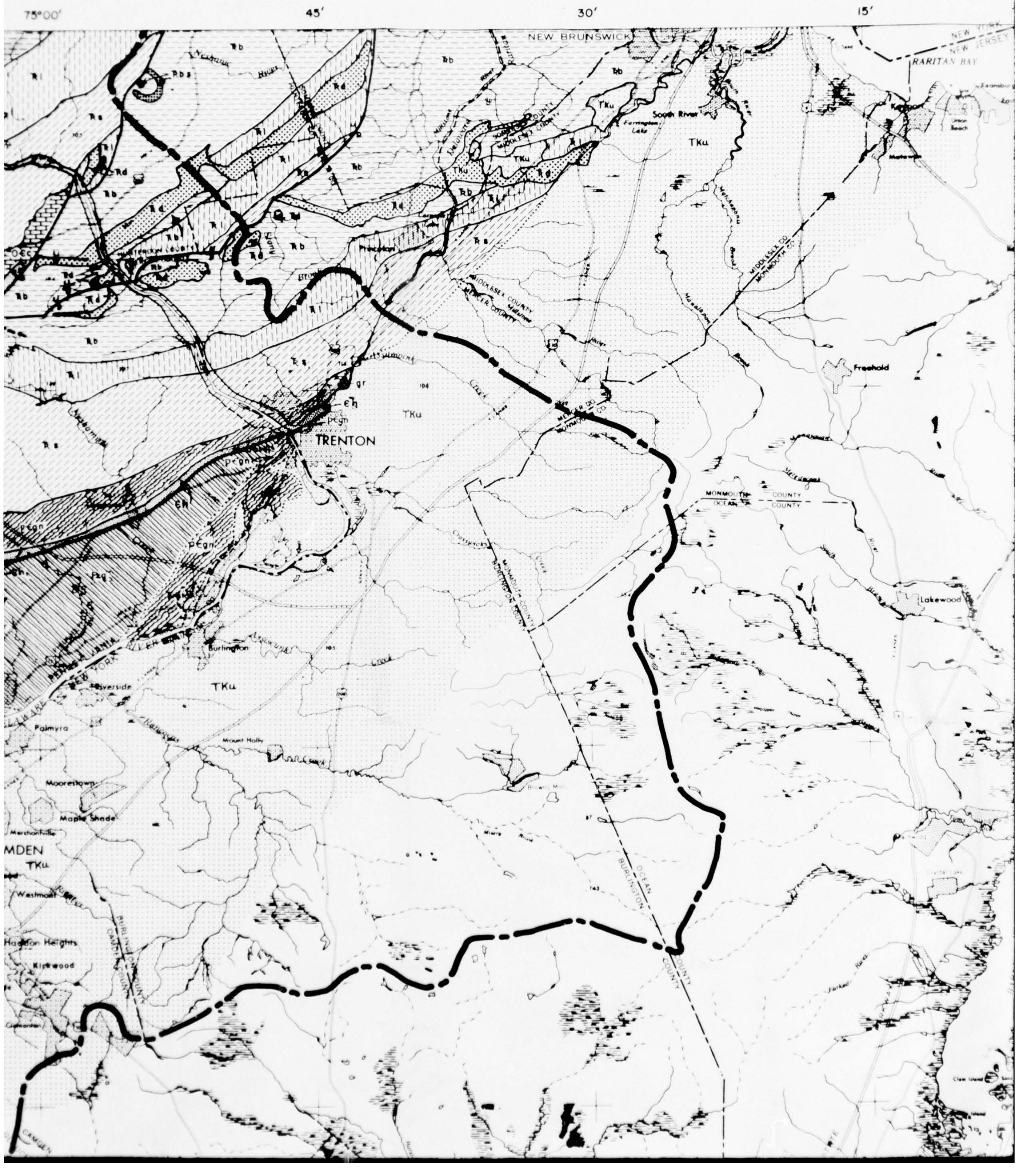
U.S. GEOLOGICAL SURVEY





45′
30′
15′
75°00′
Lansdale
NORRISTOWN
PHILADELPHIA
CAMDEN
TKu
Palmyra
Moorestown
Maple Shade
Merchantville
Collingswood
Audubon
Westmont
Gloucester
Haddon Heights
Kirkwood
Woodbury
Paulsboro
CHESTER
Wenonah
Swedesboro
Penn Grove
DELAWARE
NEW YORK

3

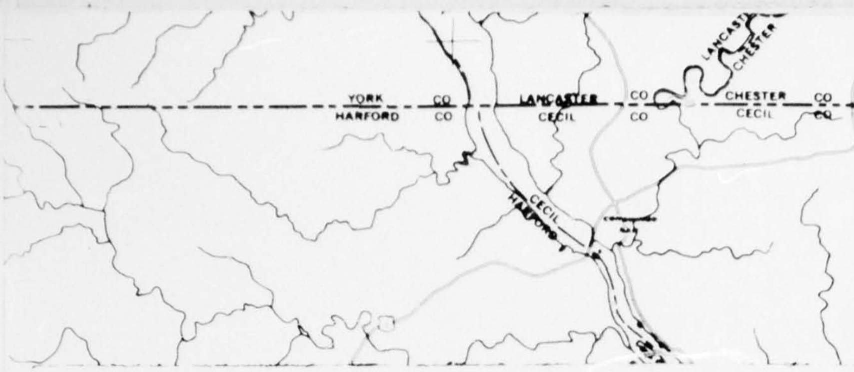


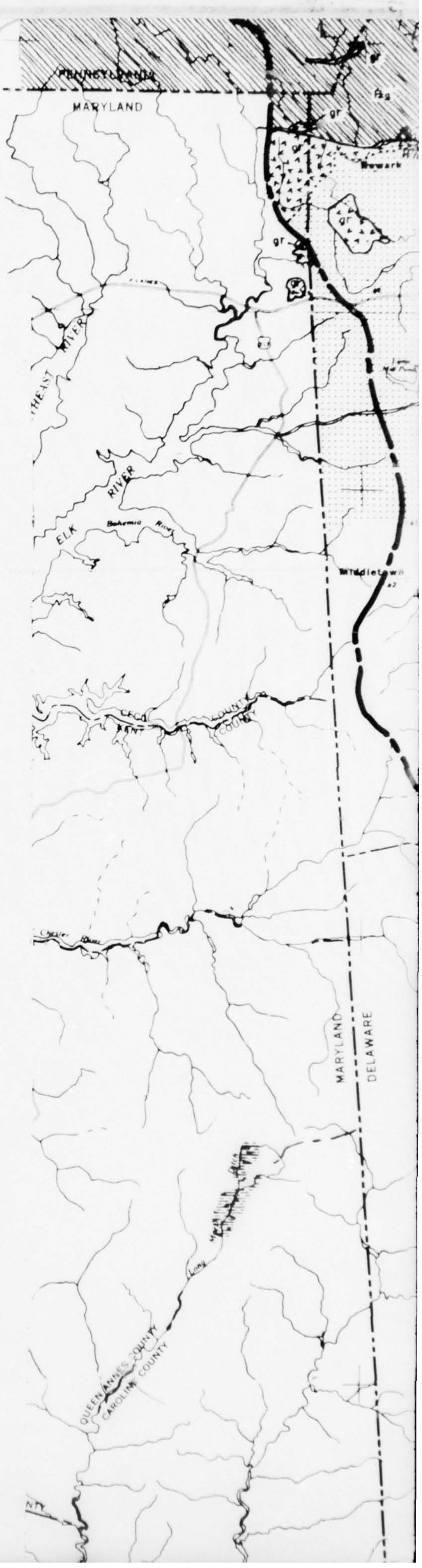
75°00'
45'
30'
15'
NEW BRUNSWICK
NEW YORK
NEW JERSEY
RARITAN BAY
South River
Farrington Lake
TKu
Princeton
MIDDLESEX COUNTY
MERCER COUNTY
MIDDLESEX CO.
MONMOUTH CO.
Freehold
TRENTON
MONMOUTH COUNTY
OCEAN COUNTY
MERCER CO.
MONMOUTH CO.
MONMOUTH COUNTY
BURLINGTON COUNTY
Lakewood
Burlington
Riverside
Palmyra
Mount Holly
Moorestown
Maple Shade
MDEN
Westmont
Haddon Heights
Kirkwood
BURLINGTON COUNTY
CAMDEN COUNTY
OCEAN
BURLINGTON
COUNTY
COUNTY
DELAWARE
PENNSYLVANIA
NEW YORK
CAMDEN

4

PLATE II

30′
15′
74°00′
73°50′
40°30
15′
40°00′
45′
NEW BRUNSWICK
NEW YORK
NEW JERSEY
RARITAN BAY
False Hook Channel
Keansburg
East Keansburg
SANDY HOOK
Sandy Hook Bay
Spermaceti Cove
Union Beach
Atlantic Highlands
Belford
Plum Island
Matawan
South River
Farrington Lake
TKu
Fair Haven
Red Bank
Long Branch
Freehold
Asbury Park
Allenhurst
Ocean Grove
Bradley Beach
Neptune
Belmar
Spring Lake
Manasquan
Point Pleasant
Lakewood
MIDDLESEX CO.
MONMOUTH CO.
MIDDLESEX COUNTY
MERCER COUNTY
MONMOUTH COUNTY
OCEAN COUNTY
BURLINGTON
BAY
BARNEGAT
Lavallette
Beach
Island





EXPLANATION

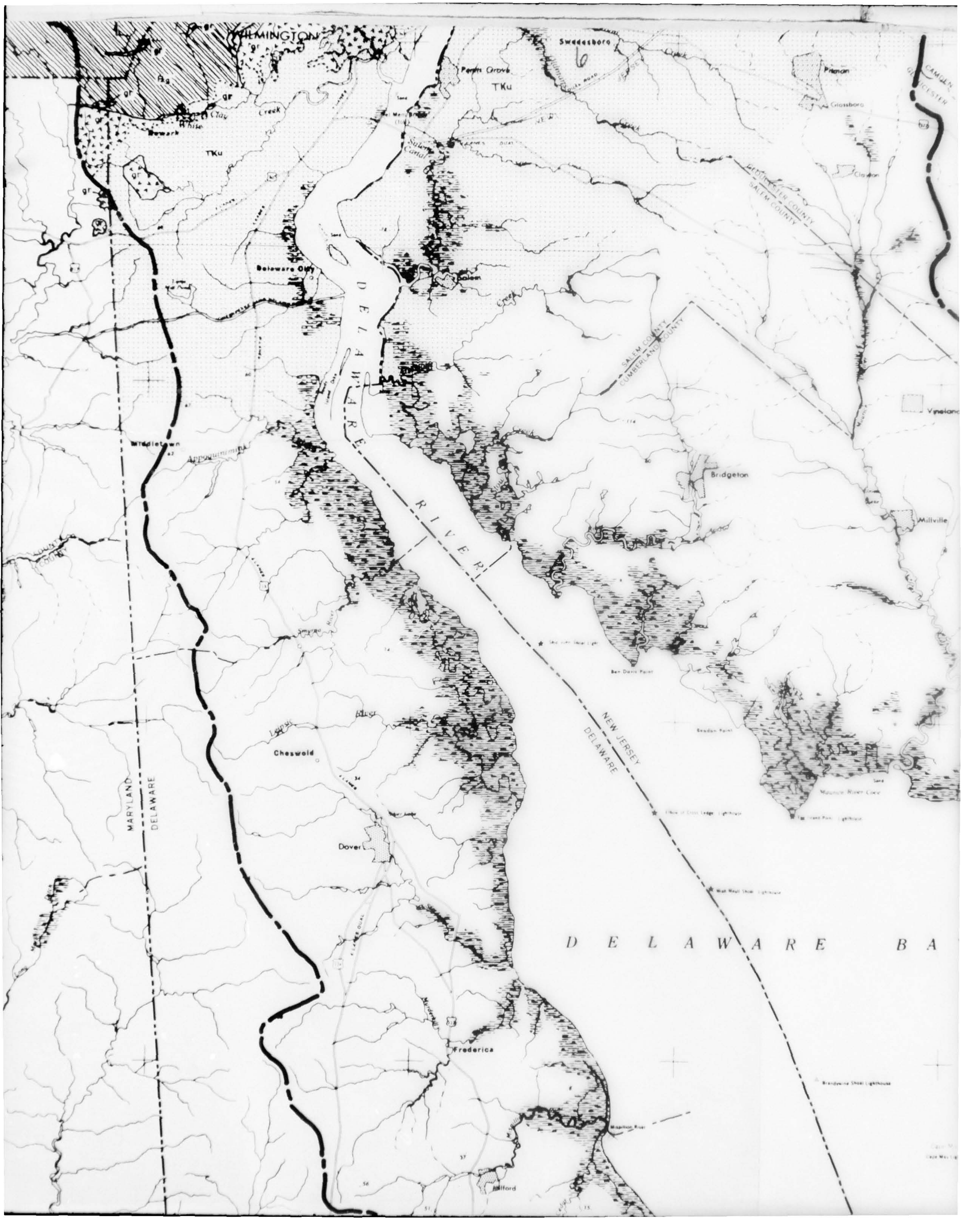
Unconsolidated sediments of Quaternary age omitted from this map; are shown on plate 7

		TKu Sediments, undifferentiated *Sand, clay, silt, marl and gravel overlying consolidated rocks in Coastal Plain. Formations shown on plate 6*	CRETACEOUS AND TERTIARY
Upper Triassic		**Ꞧd** Diabase *Igneous sills and dikes intruding Triassic and older rocks. Smaller dikes not shown*	TRIASSIC
Upper Triassic	Newark group	**Ꞧb, Ꞧbc** Brunswick formation *Shale and minor sandstone, Ꞧb; conglomerate, Ꞧbc*	TRIASSIC
Upper Triassic	Newark group	**Ꞧl** Lockatong formation *Argillite, shale, and minor sandstone*	TRIASSIC
Upper Triassic	Newark group	**Ꞧs** Stockton formation *Arkose, conglomerate, and shale*	TRIASSIC
Middle and Upper Ordovician		**Om** Martinsburg shale *Shale, slate, sandstone, and some limestone*	ORDOVICIAN
Lower Cambrian to Middle Ordovician		**O€c** Carbonate rocks *Includes Jacksonburg, Conestoga, Beekmantown, and Conococheague limestones, Allentown limestone of Wherry (1909), Limeport limestone of Howell, Roberts, and Willard (1950), Leithsville formation, and Elbrook limestone, Tomstown and Ledger dolomites, Kinzers formation, and Vintage dolomite*	CAMBRIAN AND ORDOVICIAN
Lower Cambrian		**€h** Quartzose rocks *Includes Antietam sandstone, Harpers schist, Chickies quartzite including Hellam conglomerate member, and Hardyston quartzite*	CAMBRIAN
Lower Paleozoic(?)		**Pzg, Pzgc** Glenarm series *Includes Peters Creek schist and Wissahickon formation, Pzg; Cockeysville marble, Pzgc; and Setters formation, Pzg*	PALEOZOIC

30′

15′

39°00′



WILMINGTON
Swedesboro
6
Penns Grove
TKu
Glassboro
Newark
White Clay Creek
Salem Canal
Delaware City
Salem
DELAWARE RIVER
SALEM COUNTY
CUMBERLAND COUNTY
GLOUCESTER COUNTY
SALEM COUNTY
Vineland
Middletown
Appoquinimink
Bridgeton
Millville
Smyrna River
Ben Davis Point
Cheswold
NEW JERSEY
DELAWARE
MARYLAND
DELAWARE
Maurice River Cove
Dover
DELAWARE BA
Frederica
Brandywine Shoal Lighthouse
Mispillion River
Milford

Glassboro
Clayton
CAMDEN COUNTY
GLOUCESTER COUNTY
Hammonton
Vineland
Millville
ATLANTIC COUNTY
CAPE MAY COUNTY
CUMBERLAND COUNTY
Pleasantville
Brigantine City
Absecon Inlet
ATLANTIC CITY
Ventnor
Margate City
Great Egg Inlet
Ocean City
Corson Inlet
Townsend Inlet
Great Sound
Hereford Inlet
North Wildwood
Wildwood
Cape May Inlet
Cape May
GREAT BAY
Seven Islands
LITTLE EGG HARBOR
GARDEN STATE
BAY
ATLANTIC


8
Manahawkin Bay
Surf City
Brant Beach
Spray Beach
Beach Haven
LITTLE EGG HARBOR
GREAT BAY
Seven Islands
GARDEN STATE
Reed Bay
Pleasantville
Absecon Bay
Brigantine City
Absecon Inlet
ATLANTIC CITY
Ventnor
Margate City
Great Egg Inlet
Ocean City
Corson Inlet
ATLANTIC OCEAN
30′
15′
39°00′

Middle and Upper Ordovician | ORDOVICIAN

Om

Martinsburg shale

Shale, slate, sandstone, and some limestone

Lower Cambrian to Middle Ordovician | CAMBRIAN AND ORDOVICIAN

OЄc

Carbonate rocks

Includes Jacksonburg, Conestoga, Beekmantown, and Conococheague limestones, Allentown limestone of Wherry (1908), Limeport limestone of Howell, Roberts, and Willard (1950), Leithsville formation, and Elbrook limestone, Tomstown and Ledger dolomites, Kinzers formation, and Vintage dolomite

Lower Cambrian | CAMBRIAN

Єh

Quartzose rocks

Includes Antietam sandstone, Harpers schist, Chickies quartzite including Hellam conglomerate member, and Hardyston quartzite

Lower Paleozoic(?) | PALEOZOIC

Pzg Pzgc

Glenarm series

Includes Peters Creek schist and Wissahickon formation, Pzg; Cockeysville marble, Pzgc; and Setters formation, Pzg

PRECAMBRIAN AND PALEOZOIC

um

Ultramafic rocks

Chiefly serpentine, metapyroxenite, and metaperidotite

gr

Granitic to gabbroic rocks

Medium to coarse-grained crystalline rocks of both igneous and metamorphic origin. Not differentiated from gneiss of Precambrian age or from Glenarm series where intimately or gradationally associated with those units

PRECAMBRIAN

pЄgn

Gneiss and related crystalline rocks

Chiefly gneissose rocks of metasedimentary, metaigneous, and igneous origin. Includes Pochuck gabbro gneiss, Losee diorite gneiss, Byram granite gneiss, Pickering and Baltimore gneisses, and several kinds of unnamed gneiss

Geologic contact

Dashed where uncertain; dotted where concealed

Fault

Dashed where uncertain

U, upthrown side; D, downthrown side

Boundary of Delaware River basin

39°00'

45'

30'

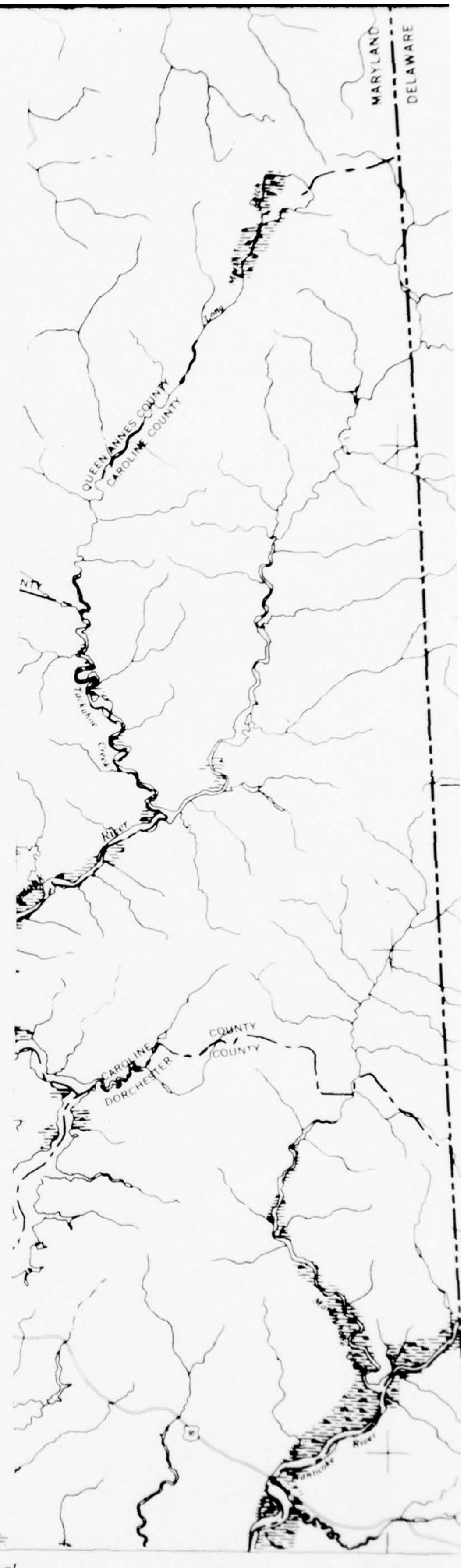
38°27'

76°30'

15'

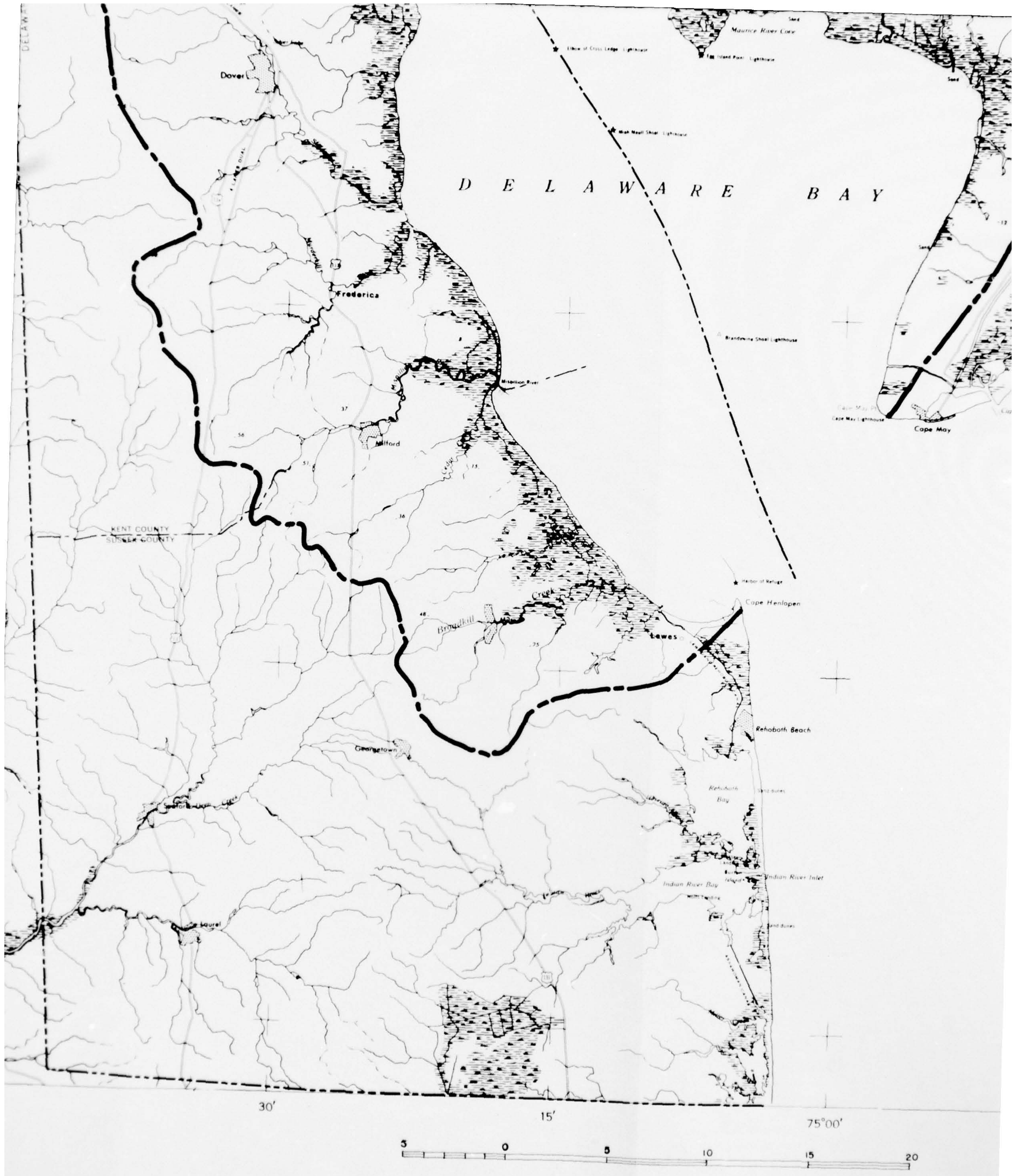
76°00'

45'



9

GEOLOGIC MAP OF SOUTH HALF OF DELAW

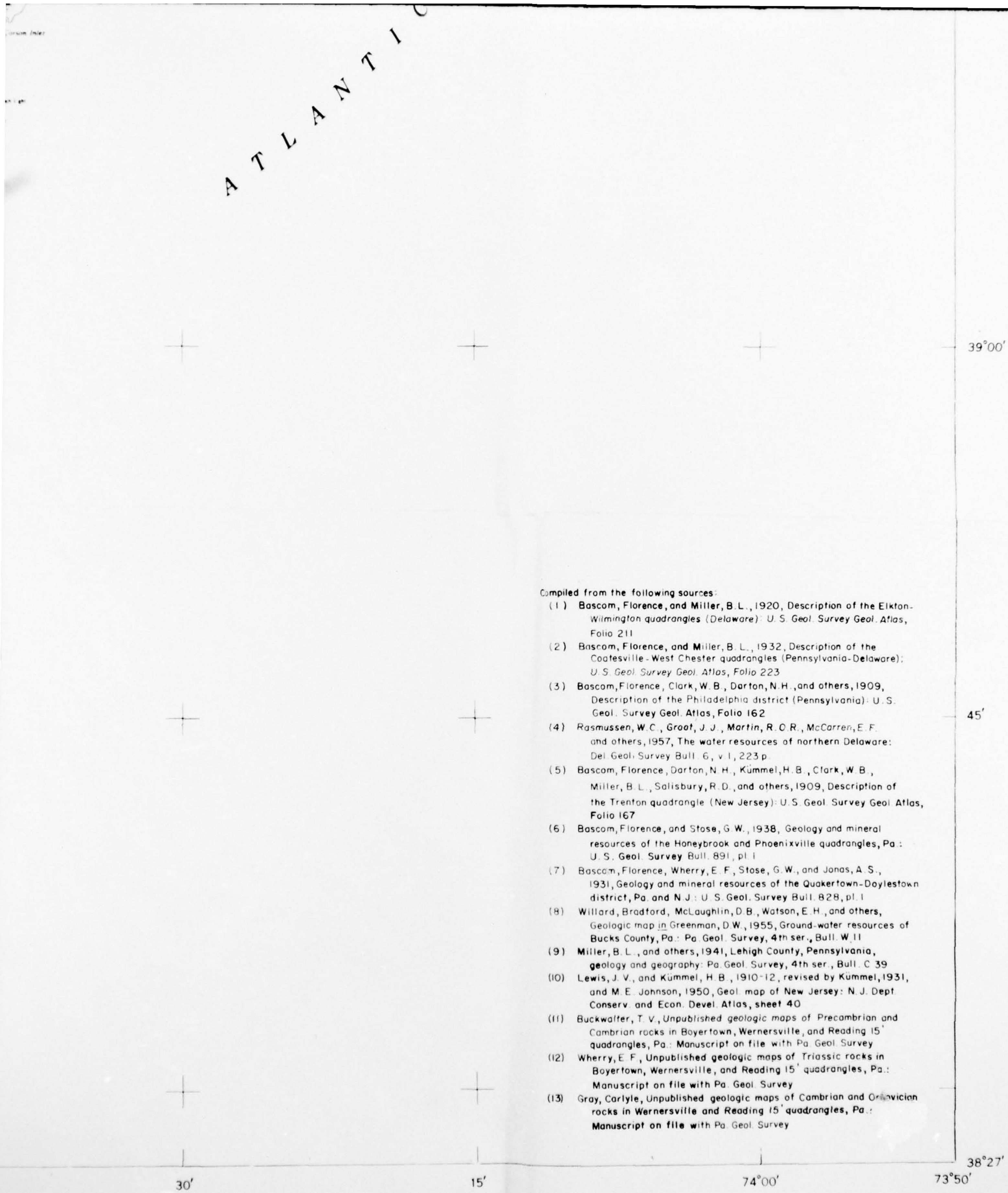


...WARE RIVER BASIN AND SOUTHERN NEW JERSEY SHO...

10

ERSEY SHOWING CONSOLIDATED ROCKS OF PRE-CRETA

11



Compiled from the following sources:

(1) Bascom, Florence, and Miller, B. L., 1920, Description of the Elkton-Wilmington quadrangles (Delaware): *U. S. Geol. Survey Geol. Atlas*, Folio 211

(2) Bascom, Florence, and Miller, B. L., 1932, Description of the Coatesville-West Chester quadrangles (Pennsylvania-Delaware): *U. S. Geol. Survey Geol. Atlas, Folio 223*

(3) Bascom, Florence, Clark, W. B., Darton, N. H., and others, 1909, Description of the Philadelphia district (Pennsylvania): U. S. Geol. Survey Geol. Atlas, Folio 162

(4) *Rasmussen, W. C., Groot, J. J., Martin, R. O. R., McCarren, E. F.* and others, 1957, The water resources of northern Delaware: Del. Geol. Survey Bull. 6, v. 1, 223 p.

(5) Bascom, Florence, Darton, N. H., Kümmel, H. B., Clark, W. B., Miller, B. L., Salisbury, R. D., and others, 1909, Description of the Trenton quadrangle (New Jersey): U. S. Geol. Survey Geol. Atlas, Folio 167

(6) Bascom, Florence, and Stose, G. W., 1938, Geology and mineral resources of the Honeybrook and Phoenixville quadrangles, Pa.: U. S. Geol. Survey Bull. 891, pl. 1

(7) Bascom, Florence, Wherry, E. F., Stose, G. W., and Jonas, A. S., 1931, Geology and mineral resources of the Quakertown-Doylestown district, Pa. and N. J.: U. S. Geol. Survey Bull. 828, pl. 1

(8) Willard, Bradford, McLaughlin, D. B., Watson, E. H., and others, Geologic map in Greenman, D. W., 1955, Ground-water resources of Bucks County, Pa.: Pa. Geol. Survey, 4th ser., Bull. W 11

(9) Miller, B. L., and others, 1941, Lehigh County, Pennsylvania, geology and geography: Pa. Geol. Survey, 4th ser., Bull. C 39

(10) Lewis, J. V., and Kümmel, H. B., 1910-12, revised by Kümmel, 1931, and M. E. Johnson, 1950, Geol. map of New Jersey: N. J. Dept. Conserv. and Econ. Devel. Atlas, sheet 40

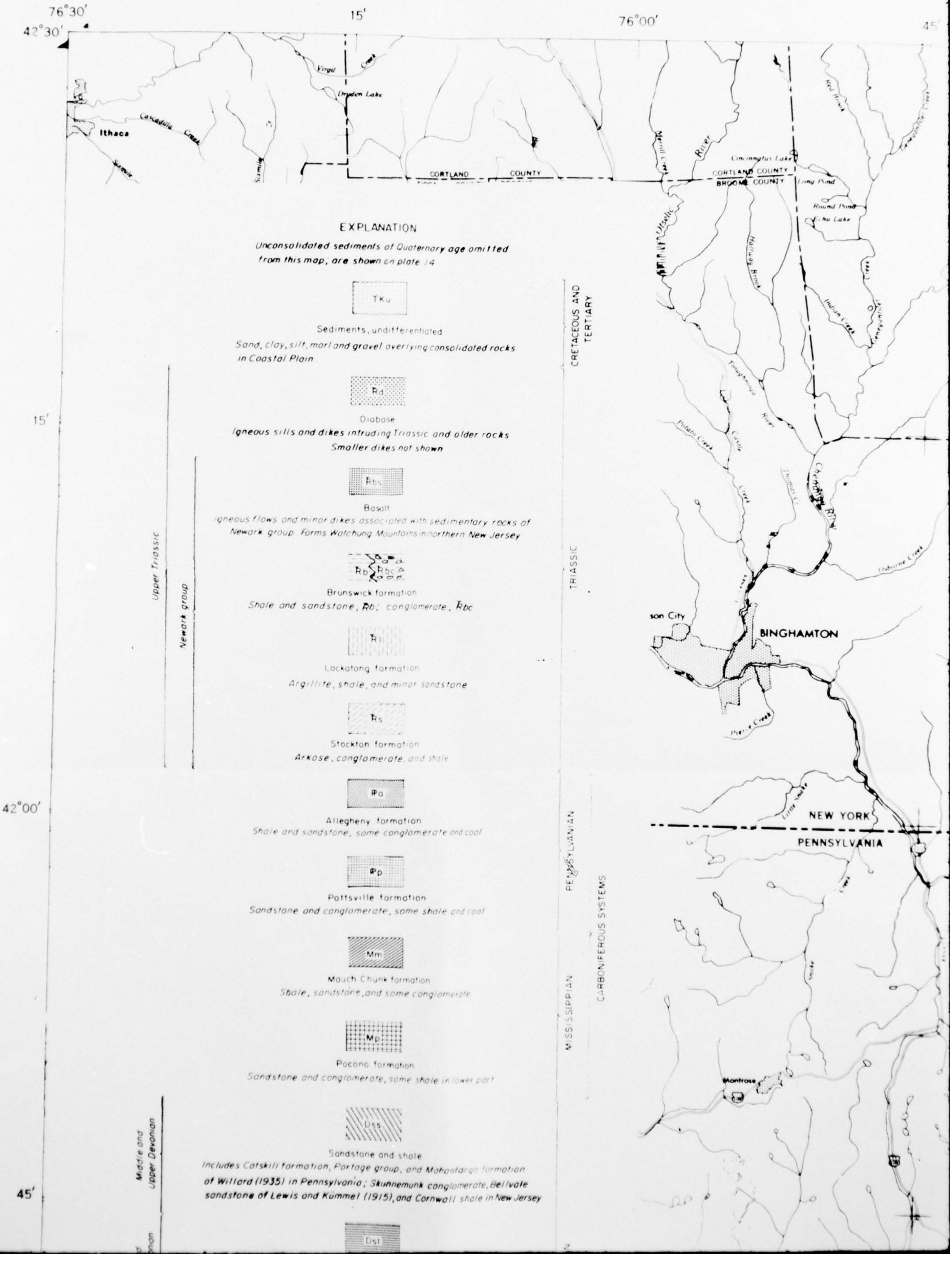
(11) Buckwalter, T. V., *Unpublished geologic maps of* Precambrian and Cambrian rocks in Boyertown, Wernersville, and Reading 15′ quadrangles, Pa.: Manuscript on file with Pa. Geol. Survey

(12) Wherry, E. F., Unpublished geologic maps of Triassic rocks in Boyertown, Wernersville, and Reading 15′ quadrangles, Pa.: Manuscript on file with Pa. Geol. Survey

(13) Gray, Carlyle, Unpublished geologic maps of Cambrian and Ordovician rocks in Wernersville and Reading 15′ quadrangles, Pa.: Manuscript on file with Pa. Geol. Survey

SOLIDATED ROCKS OF PRE-CRETACEOUS AGE

U. S. GEOLOGICAL SURVEY



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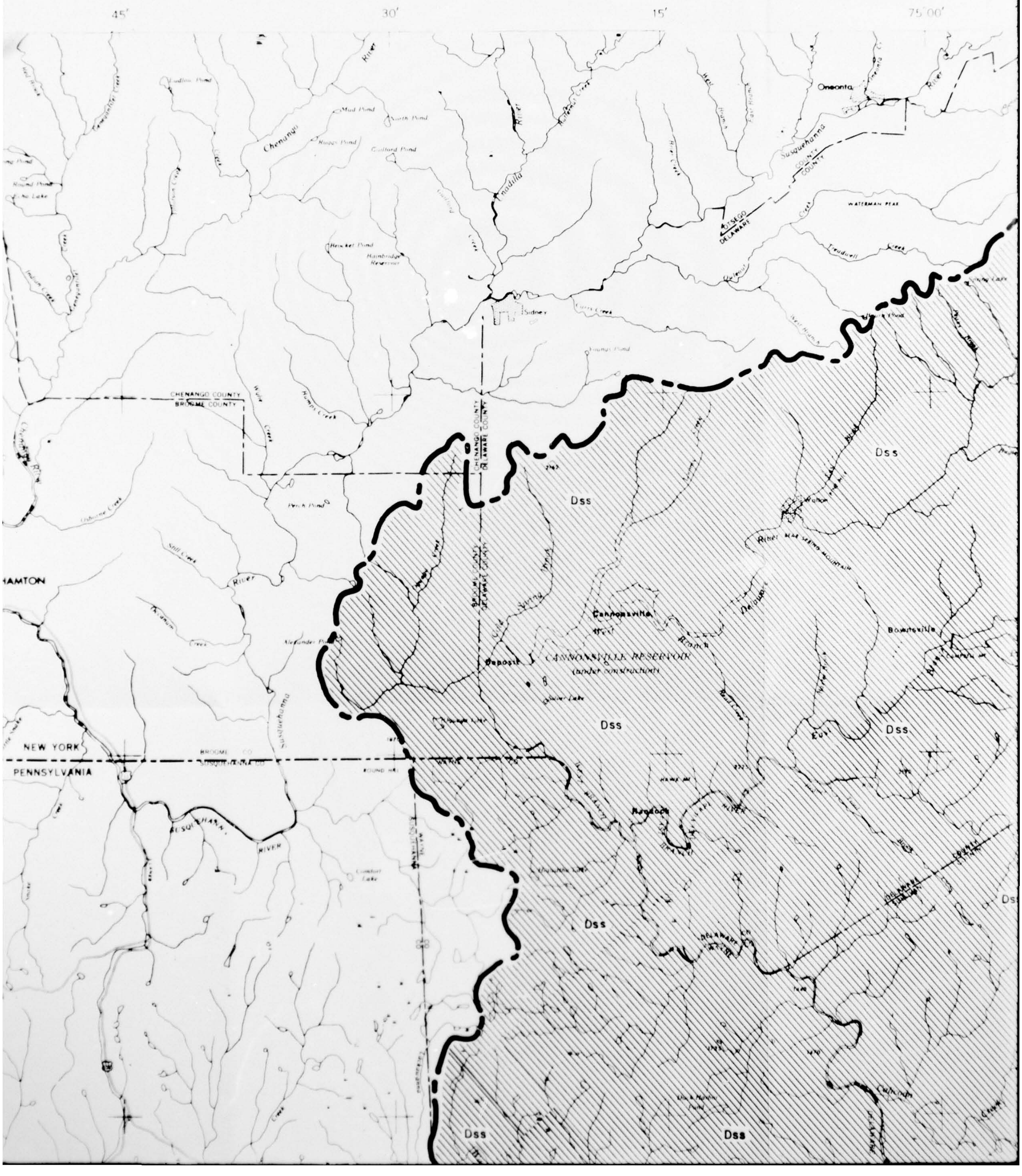
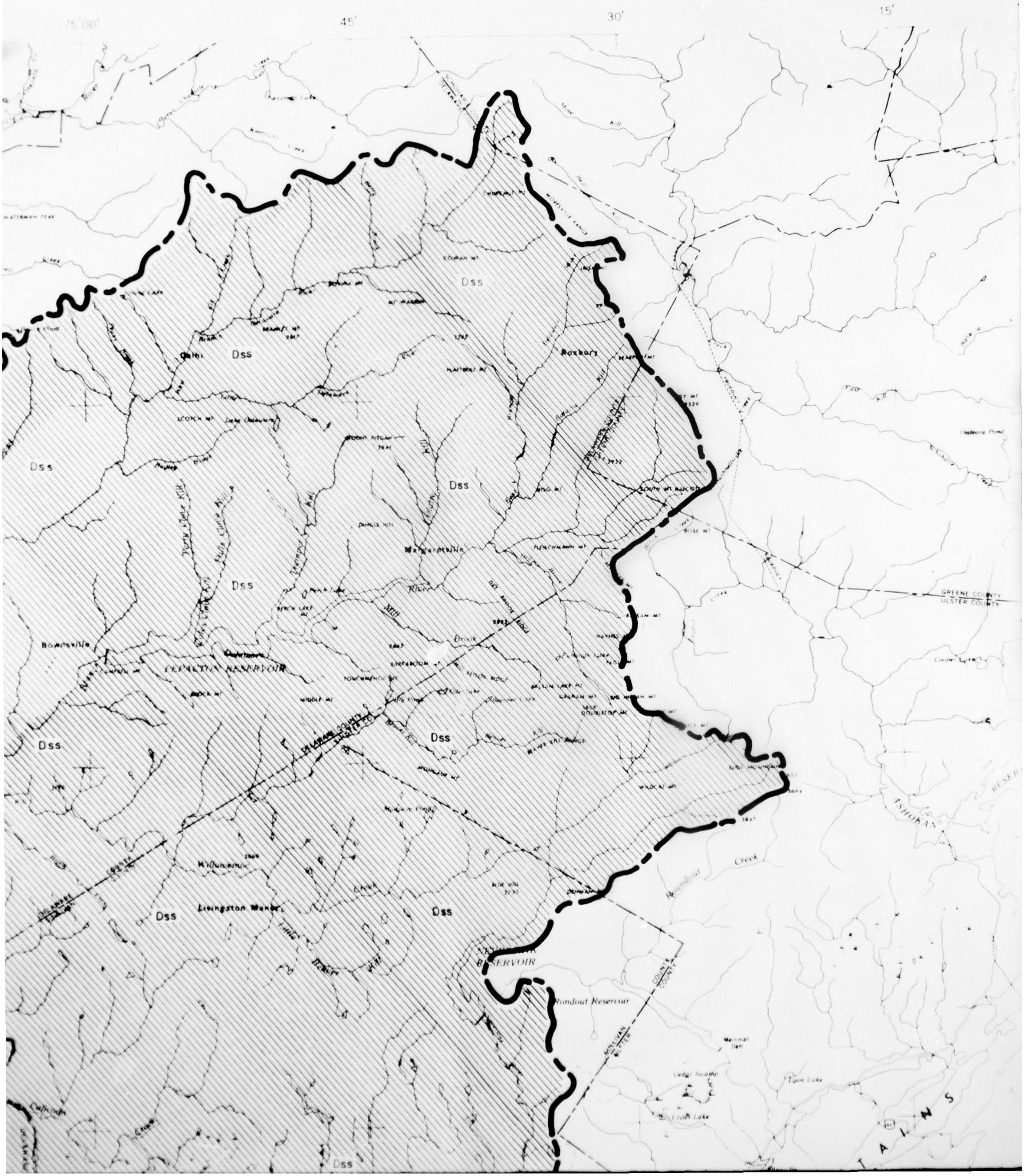


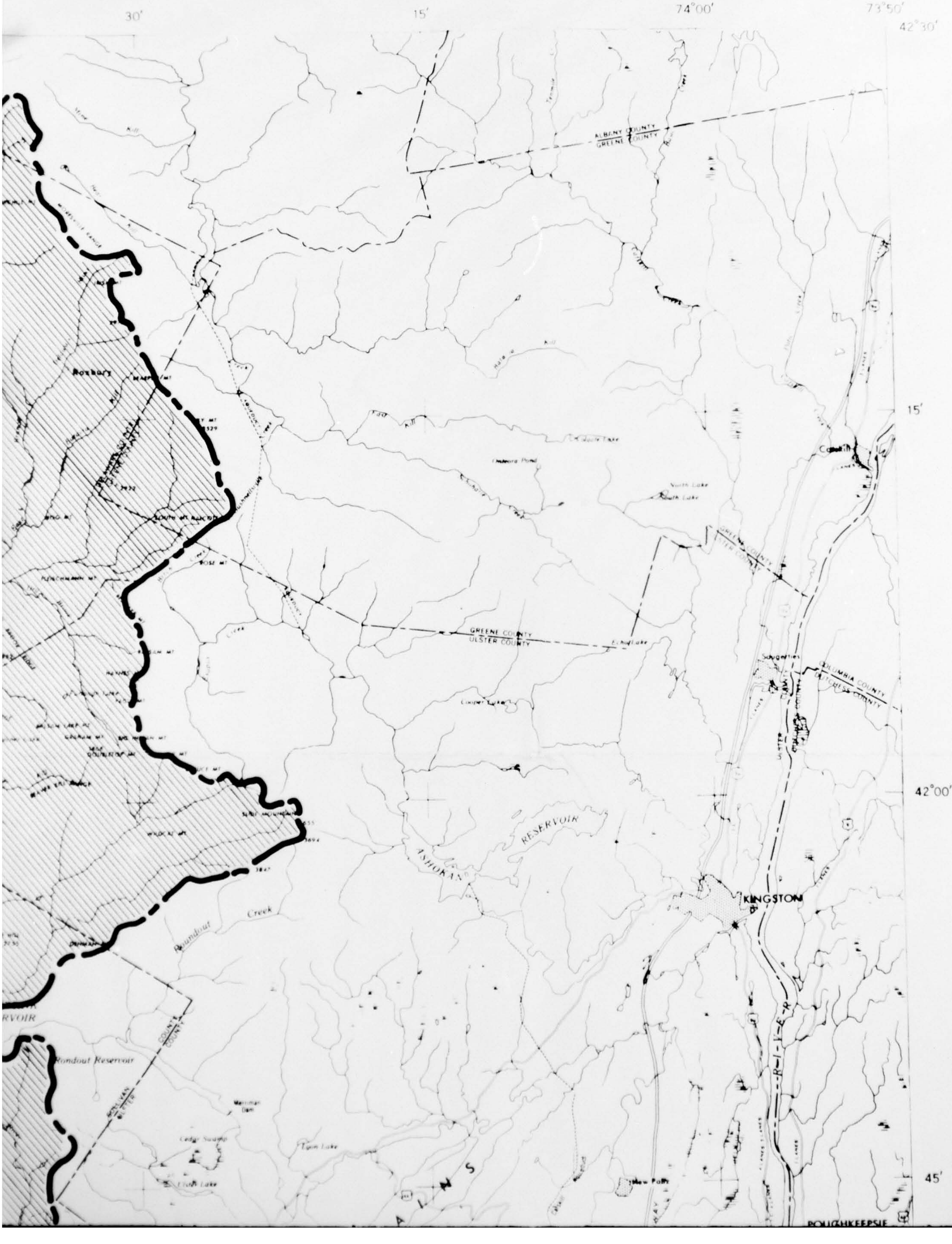
45'
30'
15'
75°00'
Oneonta
Chenango
Sidney
CHENANGO COUNTY
BROOME COUNTY
HAMTON
Dss
Cannonsville
Deposit
CANNONSVILLE RESERVOIR
(under construction)
NEW YORK
PENNSYLVANIA
BROOME CO
SUSQUEHANNA CO
WATERMAN PEAK
OTSEGO
DELAWARE

3


45'
30'
15'
Dss
Roxbury
Margaretville
PEPACTON RESERVOIR
DELAWARE COUNTY
GREENE COUNTY
ULSTER COUNTY
Cooper Lake
ASHOKAN
Rondout Creek
Rondout Reservoir
Livingston Manor
Cedar Swamp
Downsville

4

PLATE 12


30'
15'
74°00'
73°50'
42°30'
15'
42°00'
45'
ALBANY COUNTY
GREENE COUNTY
GREENE COUNTY
ULSTER COUNTY
COLUMBIA COUNTY
DUTCHESS COUNTY
Roxbury
North Lake
South Lake
Echo Lake
Cooper Lake
Saugerties
ASHOKAN
RESERVOIR
KINGSTON
Rondout Creek
Rondout Reservoir
New Paltz
POUGHKEEPSIE
RIVER

5

45′

Middle and Upper Devonian

Sandstone and shale

Includes Catskill formation, Portage group, and Mahantango formation of Willard (1935) in Pennsylvania; Skunnemunk conglomerate, Bellvale sandstone of Lewis and Kümmel (1915), and Cornwall shale in New Jersey

Lower and Middle Devonian

Dsl

Shale and limestone

Includes Marcellus shale, Onondaga limestone, and Esopus shale, and also Kanouse sandstone in north-central New Jersey

DEVONIAN

Lower Devonian

Do

Oriskany sandstone

Sandstone and some shale and cherty limestone in New Jersey includes Esopus

Upper Silurian and Lower Devonian

DS

Limestone, shale, and sandstone

Includes Helderberg group, Manlius, Rondout, Decker, and Bossardsville limestones, and Wills Creek shale

SILURIAN AND DEVONIAN

30′

Upper Silurian

Sb

Bloomsburg red beds

Red shale and sandstone Includes High Falls formation and Longwood shale in New Jersey, and High Falls shale and Binnewater sandstone of Grabau (1906) in New York

SILURIAN

Ss

Shawangunk conglomerate

Conglomerate, sandstone, and some shale in north-central New Jersey, includes Green Pond conglomerate

Middle and Upper Ordovician

Om

Martinsburg shale

Shale, slate, sandstone, and some limestone In New York, includes Snake Hill formation and Normanskill shale

ORDOVICIAN

Lower Cambrian to Middle Ordovician

O€c

Carbonate rocks

Includes Jacksonburg and Beekmantown limestones, Allentown limestone of Wherry (1909), Limeport limestone of Howell, Roberts, and Willard (1950), Leithsville limestone, and Tomstown dolomite

CAMBRIAN AND ORDOVICIAN

15′

Lower Cambrian

€h

Hardyston quartzite

Hard sandstone and quartzite, and some conglomerate, slate, and limestone

CAMBRIAN

p€f

Franklin limestone

Coarse white crystalline limestone, in part dolomitic

p€gn

Gneiss and related crystalline rocks

Chiefly gneissose rocks of metasedimentary, metaigneous, and igneous origin includes Pochuck gabbro gneiss, Losee diorite gneiss, Byram granitic gneiss, several kinds of unnamed gneissose rocks, and complexly associated granitic to ultramafic rocks

PRECAMBRIAN

Geologic contact

Dashed where uncertain, dotted where concealed

U

D

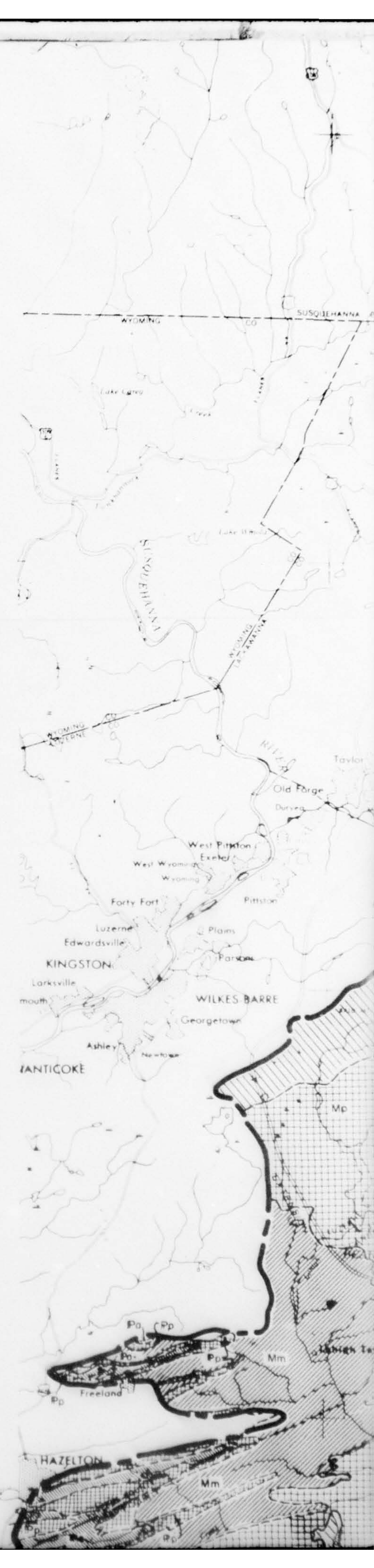
Fault

Dashed where uncertain

U, upthrown side; D, downthrown side

41°00′

Boundary of Delaware River basin



60
Dss
Dss
SUSQUEHANNA
LACKAWANNA
PROMPTON F.C. RESERVOIR
(under construction)
DYBERRY F.C. RESERVOIR
(under construction)
Simpson
Carbondale
Mayfield
Jermyn
Honesdale
Dss
Dss
Peckville
Winton
Dickson City
Olyphant
Throop
Dunmore
SCRANTON
Taylor
Old Forge
Pittston
Dss
BARRE
Mp
Mp
Dss
Dss
Mm
Mp
Mp
Sb
Ss
Om
DS
Dsl
Oec
Do
DS
Sb
Om
DS
PENN FOREST RESERVOIR

MOUNTAINS
Ellenville
Middletown
Goshen
Monroe
NEWBUR
Greenwood Lake
NEW YORK
NEW JERSEY
PENNSYLVANIA
Dss
Ds
Do
Dsl
Ss
Sb
Om
Oec
Єh
pЄgn
gn

8

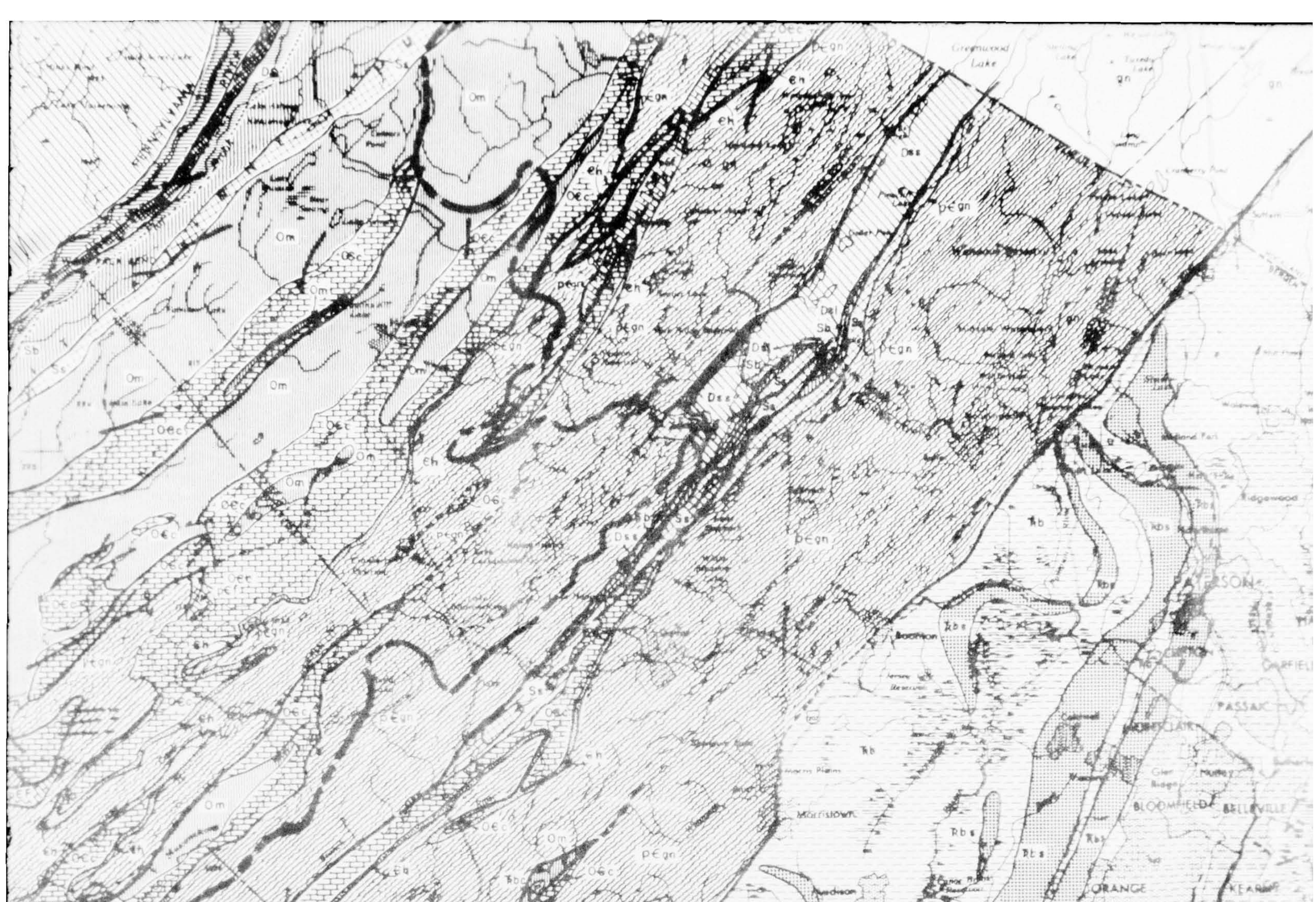

7
MOUNTAINS
POUGHKEEPSIE
New Paltz
Ellenville
NEW YORK THRUWAY
ULSTER COUNTY
ORANGE COUNTY
Walden
NEWBURGH
Beacon
DUTCHESS COUNTY
PUTNAM COUNTY
Middletown
Goshen
Monroe
Peekskill
ORANGE COUNTY
ROCKLAND COUNTY
NEW YORK
NEW JERSEY
Greenwood Lake
Haverstraw
Croton on Hudson
Ossining
Spring Valley
Suffern
Nyack
Tarrytown
Park Ridge
Ridgewood
Dobbs Ferry
Hastings on Hudson
45'
30'
15'
41°00'

GEOLOGIC MAP OF NORTH HALF OF DELAWAR

9

LAWARE RIVER BASIN AND NORTHERN NEW JERSEY SHO

10



RSEY SHOWING CONSOLIDATED ROCKS OF PRE-CRETACE

11

IDATED ROCKS OF PRE-CRETACEOUS AGE

12

DATE
FILME